Searches for the Standard Model Higgs Boson at the Tevatron

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Argonne National Laboratory
HEP Lunch Seminar
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http://www-cdf.fnal.gov/physics/new/hdg/Results.html
http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm
http://tevnphwg.fnal.gov/
The main problems for the SM show up in the Higgs sector

\[ V_{Higgs} = V_0 - \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 + [\bar{\psi}_L Y_{ij} \psi_{Rj} \phi + h.c.] \]

- Vacuum energy \( V_{0\text{exp}} \sim (2.10^{-3} \text{ eV})^4 \)
- Possible instability depending on \( m_H \)
- Origin of quadratic divergences. Hierarchy problem
- The flavour problem: large unexplained ratios of \( Y_{ij} \) Yukawa constants
With no Higgs unitarity violations for $E_{\text{CM}} \sim 1$-$3$ TeV

Unitarity implies that scattering amplitudes cannot grow indefinitely with the centre-of-mass energy $s$.

In the SM, the Higgs particle is essential in ensuring that the scattering amplitudes with longitudinal weak bosons ($W_L, Z_L$) satisfy (tree-level) unitarity constraints.

[Veltman, 1977; Lee-Quigg-Thacker, 1977; ...]

An example:

$$\mathcal{A}(W_L^+ W_L^- \rightarrow Z_L Z_L) \quad (s \gg m_W^2)$$

$$\rightarrow -i \frac{m_h^2}{v^2} \frac{s}{s - m_h^2}$$

If no Higgs then something must happen!

_G. Altarelli, HCPSS 2008_
The LEP2 and Tevatron, LEP1, SLD Precision EW Legacy

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

No evidence below

Precision $m_z$, $m_W$, $m_t$, Z-pole asymmetries, etc.

$m_H^{SM} = 89^{+35}_{-26} \text{ GeV}/c^2$

http://lepewwg.web.cern.ch/LEPEWWG
http://lephiggs.web.cern.ch/LEPHIGGS/www/Welcome.html

@95% CL, $m_H < 158 \text{ GeV}/c^2$

(185 including LEP2 direct limit)
Vacuum Stability and Triviality Bounds on SM $m_H$

Loops with SM particles modify the effective Higgs potential.

Finding a Higgs boson with $m_H$ “too low” or “too high” is suggestive of new physics.

See also hep-ph/9708416
Hambye and Riesselman

Isidori, Rychkov, Strumia, Tetradis ‘08
Adding the metastable possibility: Isidori, Ridolfi, Strumia ‘01

- The unstable region is almost ruled out

[ G.I., Rychkov, Strumia, Tetradis '08]

a slide from G. Altarelli’s HCPSS 2008 talk
How Much Fine-Tuning Can We Tolerate?

\[ m_h^2 = 2\mu^2 = 4\lambda v^2 \]

At one loop,

\[ \mu^2 \rightarrow \mu^2 + \frac{\Lambda^2}{32\pi^2 v^2} (2M_W^2 + M_Z^2 + m_h^2 - 4m_t^2) \]

If the radiative corrections to \( m_h \) are not >> \( m_h \), we get much stronger constraints. “Veltman Condition”: term in parentheses vanishes.

C. Kolda and H. Murayama, JHEP 0007, 035 (2000)

\( m_t = 175 \text{ GeV} \)
At one-loop, the Higgs boson couples to gluons via a loop of quarks:

This diagram leads to an effective Lagrangian

\[ \mathcal{L}_{hgg}^{\text{eff}} = \frac{g\alpha_s N_g}{24\pi m_W} h^0 q^a G_{\mu
u}^a G^{\mu\nu} , \]

where \( N_g \) is roughly the number of quarks heavier than \( h^0 \). More precisely,

\[ N_g = \sum_i F_{1/2}(x_i), \quad x_i = \frac{m_{q_i}^2}{m_h^2} , \]

where the loop function \( F_{1/2}(x) \rightarrow 1 \) for \( x \gg 1 \).

A heavy fourth generation of quarks would scale the \( gg \rightarrow H \) production rate at colliders by a factor of \( \sim 9 \). But watch out for \( H \rightarrow \nu_4 \bar{\nu}_4 \) decays.

gg→H Production at NNLO

• NLO corrections -- ~80% (almost double the LO cross section)!
• NNLO QCD corrections -- An additional 40% on top of that!
• Soft gluon resummation included at NNLL in plots below

NLO,NNLO bands: 0.5m_H<\mu_F,\mu_R<2M_H. Bands on LO unreliable.
Recent gg→H Production Cross Section Progress

An active area of research over the last years

http://www.itp.uzh.ch/events/higgsboson2009 7-9 January 2009, Zurich

• Two-loop EW corrections yield up to an 6% boost in cross section near $m_H=160$ GeV. Aglietti, Bonciani, Degrassi and Vicini, arXiv:hep-ph/0610033 (used by the Tevatron at ICHEP 2008)

• Newer calculations: Anastasiou, Boughezal, Petriello, JHEP 0904:003 (2009)

More modern PDF set -- MSTW 2008 NNLO (lost 14% of cross section rel. to MRST 2006 NNLO)

Bottom quark loops interfere destructively with top quark loops
  • Bottom quark loop contributions get smaller QCD corrections than top loops.
  • Running $b$ mass is smaller than pole mass.

Less contribution from $b$ loops means more cross section

Coincidentally almost the same cross section relative to NNLO QCD (Catani et. al) at $m_H=160$ GeV -- 0.44 pb at the Tevatron.
EW corrections to $\sigma(gg\to H)$

Passarino, Higgs Boson 2009, Zurich

Tevatron SM Higgs Searches T. Junk ANL 19 Oct 2010
Choosing the Right Factorization and Renormalization Scale and Uncertainty

C. Anastasiou, Orsay 2010 (www.higgshunting.fr).

- Several points cleared up with Baglio and Djouadi – concerns raised in arXiv:1003.4266
  - Best scales are low – $m_{H}/2$ provides much more stability for fixed-order calc's
  - Setting $\mu_{r} = \mu_{f}$ gives the largest variation in cross section and makes more sense than exploring the $(\mu_{r}, \mu_{f})$ plane
Perturbative series converges faster when a more detailed calculation is performed:

- RG improvement
- soft-gluon resummation
- using the PDF set which corresponds to each order

- LO calculation with no gluon emission isn’t sufficiently sensitive to the scale to trust it to gauge scale uncertainty

Ahrens, Becher, Neubert, Yang 2010

Tevatron SM Higgs Searches T. Junk ANL 19 Oct 2010
At $\mu_r = \mu_f = m_H/2$, the NNLL addition to the NNLO cross section is negligible.
Missing higher orders?

- A small scale leads to a faster convergence from NLO to NNLO.

- Are we missing even higher order effects?

- A lot is known from threshold resummation methods.

- Small mu scales are safe!

Slide from C. Anastasiou, higgshunting.fr

It does not look as if there are large negative contributions at much higher order, and a scale of $m_H/2$ seems stable.
Parton Distribution Functions of the Proton

MSTW 2008 NLO PDFs (68% C.L.)

\[ Q^2 = 10 \text{ GeV}^2 \]

\[ Q^2 = 10^4 \text{ GeV}^2 \]

\[ x f(x, Q^2) \]

\[ x f(x, Q^2) \]
SM Higgs Boson Production Mechanisms


Tevatron SM Higgs Searches T. Junk ANL 19 Oct 2010
Which PDF Sets to Use?

Baglio and Djouadi suggest taking the difference in the predictions of \( gg \rightarrow H \) using ABKM09 and MSTW2008, CTEQ2008 PDF’s as a systematic uncertainty.
Variations in Predictions for Different PDF Sets

R. Thorne, Higgs Hunting Orsay Workshop, 2010
ABKM and HERAPDF do not include Tevatron high-$E_T$ jet data in their fits. High-$x$ gluons are poorly constrained without those.

Very Measurable! (but need luminosity!)

PDF4LHC recommendation: Use CTEQ, MSTW, NNPDF as an envelope.

R. Thorne, Higgs Hunting Orsay Workshop, 2010
ABKM and HERAPDF do not include Tevatron high-$E_T$ jet data in their fits. High-$x$ gluons are poorly constrained without those.
**gg\(\rightarrow\)H Cross Section Theoretical Uncertainties**

- Recent Work: Anastasiou, Dissertori, Grazzini, Stockli, and Webber
  JHEP 0908 099 (2009).

Factorization and Renormalization scale variations are larger when requiring 2+ jets than for requiring fewer. Errors correlated, not anticorrelated. Get worse when applying other experimental cuts.

\[
\frac{\Delta N_{\text{signal}}(\text{scale})}{N_{\text{signal}}} = 60\% \cdot \left( +\frac{5\%}{-9\%} \right) + 29\% \cdot \left( +\frac{24\%}{-23\%} \right) + 11\% \cdot \left( +\frac{91\%}{-44\%} \right) = \left( +\frac{20.0\%}{-16.9\%} \right)
\]

Scale variation is up and down by a factor of two. Djouadi (Moriond EW 2010, arXiv:1003.4266) advocates a larger variation – currently under discussion.

Experimental issue – how to incorporate?
- Traditional: Set limits on \(\sigma \times \text{Br}\). Draw theory curve on same plot with error bands. Take -1\(\sigma\) variation on theory as the excludable prediction (why?)
- We have a problem. Combine \(gg\rightarrow H\) with WH, ZH, and VBF signal searches. What’s the error on the theory band now? What cross section do we exclude?
  Solution: Treat theory uncertainties like acceptance uncertainties (when it comes to the kinematics, they are hard to separate anyhow). PDF in particular should be treated as a nuisance parameter like all others.

<table>
<thead>
<tr>
<th>(\sigma ) [fb]</th>
<th>LO (pdfs, (\alpha_s))</th>
<th>NLO (pdfs, (\alpha_s))</th>
<th>NNLO (pdfs, (\alpha_s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-jets</td>
<td>3.452(^{+7%}_{-10%})</td>
<td>2.883(^{+4%}_{-9%})</td>
<td>2.707(^{+5%}_{-9%})</td>
</tr>
<tr>
<td>1-jet</td>
<td>1.752(^{+30%}_{-26%})</td>
<td>1.280(^{+24%}_{-23%})</td>
<td>1.165(^{+24%}_{-22%})</td>
</tr>
<tr>
<td>(\geq 2)-jets</td>
<td>0.336(^{+91%}_{-44%})</td>
<td>0.221(^{+81%}_{-42%})</td>
<td>0.196(^{+78%}_{-41%})</td>
</tr>
</tbody>
</table>

Table 2: Inclusive cross sections in the different jet bins.
HqT program  Catani and Grazzini, http://theory.fi.infn.it/grazzini/codes.html used to compute higher-order differential spectra

Formerly taken as a systematic uncertainty, now is a central value.

Scale and PDF dependence of Higgs $p_T$ and $\eta$ used as rate and shape systematics
Standard Model Higgs Boson Decay Branching Fractions

HDECAY by M. Spira

114.4 < $m_H$ < 135 GeV: $H \rightarrow bb$ dominates.

$gg \rightarrow H \rightarrow bb$ drowned by $gg \rightarrow bb$. Use WH, ZH.

135 < $m_H$ < 200 GeV

$H \rightarrow W^+W^-$ dominates

$gg \rightarrow H$, WH, ZH, VBF all can be used
The Detector

Lepton coverage:

| η | < 1.5 (muons)
| η | < 2.0 (electrons)

b-tagging with

| η | < ~1.4

Jets to

| η | < 2.8

Higgs analyses restrict to

| η | < 2.0

Dijet mass resolution: ~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 → 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,μ)
- Missing transverse energy
- m_\parallel > 16 GeV (except now with a new low m_\parallel analysis from CDF)

Dominant difficult background:
qq→ W⁺W⁻

- Higgs is a Scalar! Angular correlations are different from SM W⁺W⁻ bg
- Signal leptons come out collinear
Five Years ago: 2005 CDF H→WW Analysis

- Just used gg→H signal
  
  acceptance: 0.7% of ggH, or about 0.55% of all H at 
  \( m_H = 160 \text{ GeV} \)

- Final discriminant: \( \Delta \phi_{ll} \)

- Jet vetoes to suppress ttbar

CDF Run II Preliminary, \( L_{\text{int}} = 360 \text{ pb}^{-1} \)

\[ m_H = 160 \text{ GeV} \]

Expected limit: \(~15 \times \text{SM}\) at \( m_H = 160 \text{ GeV} \)
Splitting up $H \rightarrow WW$ Into Subsamples

- Original analysis vetoed on extra jets
- But We can analyze these events one category at a time
  - $WW+0$ jets: $gg \rightarrow H$. Mostly $gg \rightarrow H$, but add in $WH, ZH, VBF$ here
    (6% more signal expectation)
  - $WW+1$ jet: $gg \rightarrow H, WH, ZH, VBF$ signals
    (20% more signal than just $gg \rightarrow H$)
  - $WW+2$ jets (or more) 60% more signal from $WH, ZH$ and $VBF$. – most of the signal! Main background is t-tbar. Veto events with b-tags and use them as a control region
  - Total CDF acceptance summer 2009: 1.1%: **DOUBLE the 2005 acceptance.** Further improvements since then!

  Comparable MET resolution for different lepton categories – $ee, e\mu, \mu\mu$ handled together. Forward leptons treated differently from central leptons since the fake rates are different. Called High s/b (central leptons) and Low s/b (forward)

  - Same-sign dileptons + one or more jets: Mostly sensitive to $WH$ and $ZH$, with leptonic $W, Z$ decay.
  - New for Summer 2010: Channels with one lepton and a hadronic tau candidate, and also two new trilepton channels

**Each major background has a dedicated control sample**
Opposite-sign, same-flavor leptons

MET<25 GeV
76<M_\ll<106 GeV
Same Sign Dilepton Control Region

\( W_\gamma, W+\text{jets} \) backgrounds

Low-\( m_\| \) Same Sign is used to constrain the \( W_\gamma \) background

\( W+\text{jets} \) data times a fake rate function gives \( W+\text{jets} \) background
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?

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

$y$=parton (or neutrino momenta), $x$=measured jet quantities.

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

Signal model: MC@NLO

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

SM: 12.4 \pm 0.7 \text{ pb (MCFM)}

CDF H→WW Opposite sign leptons, 0 Additional Jets

Final Discriminant: NN (NeuroBayes(TM)) with Matrix element, and other, inputs

<table>
<thead>
<tr>
<th>Process</th>
<th>Events/±</th>
</tr>
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<tbody>
<tr>
<td>$tt$</td>
<td>2.23 ± 0.66</td>
</tr>
<tr>
<td>$DY$</td>
<td>227 ± 62</td>
</tr>
<tr>
<td>$WW$</td>
<td>563 ± 56</td>
</tr>
<tr>
<td>$WZ$</td>
<td>25.5 ± 3.8</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>38.3 ± 5.4</td>
</tr>
<tr>
<td>$W+\text{jets}$</td>
<td>215 ± 51</td>
</tr>
<tr>
<td>$W_\gamma$</td>
<td>155 ± 22</td>
</tr>
<tr>
<td><strong>Total Background</strong></td>
<td>1226 ± 120</td>
</tr>
<tr>
<td>$gg \rightarrow H$</td>
<td>16.9 ± 3.0</td>
</tr>
<tr>
<td>$WH$</td>
<td>0.410 ± 0.070</td>
</tr>
<tr>
<td>$ZH$</td>
<td>0.416 ± 0.059</td>
</tr>
<tr>
<td>$VBF$</td>
<td>0.140 ± 0.028</td>
</tr>
<tr>
<td><strong>Total Signal</strong></td>
<td>17.8 ± 3.1</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>1230</td>
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</table>

CDF Run II Preliminary $\int \mathcal{L} = 5.9 \, \text{fb}^{-1}$ $M_H = 165 \, \text{GeV}/c^2$

**Tevatron SM Higgs Searches T. Junk ANL 19 Oct 2010**
CDF H→WW Opposite sign leptons, 1 Additional Jet

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
<th>Error</th>
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<tr>
<td>DY</td>
<td>218</td>
<td>49</td>
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<tr>
<td>WW</td>
<td>151</td>
<td>18</td>
</tr>
<tr>
<td>WZ</td>
<td>25.4</td>
<td>3.5</td>
</tr>
<tr>
<td>ZZ</td>
<td>10.3</td>
<td>1.5</td>
</tr>
<tr>
<td>W+jets</td>
<td>77</td>
<td>20</td>
</tr>
<tr>
<td>Wγ</td>
<td>25.1</td>
<td>4.3</td>
</tr>
<tr>
<td>Total Background</td>
<td>563</td>
<td>69</td>
</tr>
<tr>
<td>gg → H</td>
<td>8.0</td>
<td>2.4</td>
</tr>
<tr>
<td>WH</td>
<td>1.13</td>
<td>0.18</td>
</tr>
<tr>
<td>ZH</td>
<td>0.439</td>
<td>0.066</td>
</tr>
<tr>
<td>VBF</td>
<td>0.74</td>
<td>0.13</td>
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<td>Total Signal</td>
<td>10.3</td>
<td>2.5</td>
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<tr>
<td>Data</td>
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</tr>
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</table>

CDF Run II Preliminary \( \int \mathcal{L} = 5.9 \text{ fb}^{-1} \)

\( M_H = 165 \text{ GeV/c}^2 \)

![Graph showing data and histograms for different processes and background.](image-url)
CDF H→WW Opposite sign leptons, Two or More Additional Jets

CDF Run II Preliminary $\int \mathcal{L} = 5.9$ fb$^{-1}$

$M_H = 165$ GeV/c$^2$

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
<th>Error</th>
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</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>169 $\pm$ 24</td>
<td></td>
</tr>
<tr>
<td>$DY$</td>
<td>80 $\pm$ 31</td>
<td></td>
</tr>
<tr>
<td>$WW$</td>
<td>33.6 $\pm$ 6.1</td>
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</tr>
<tr>
<td>$WZ$</td>
<td>6.8 $\pm$ 1.3</td>
<td></td>
</tr>
<tr>
<td>$ZZ$</td>
<td>3.10 $\pm$ 0.57</td>
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<tr>
<td>$W+$jets</td>
<td>26.7 $\pm$ 7.5</td>
<td></td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>4.4 $\pm$ 1.2</td>
<td></td>
</tr>
</tbody>
</table>

Total Background | 324 $\pm$ 50 |

$gg \rightarrow H$ | 2.6 $\pm$ 1.8 |
$WH$ | 2.50 $\pm$ 0.35 |
$ZH$ | 1.28 $\pm$ 0.17 |
$VBF$ | 1.37 $\pm$ 0.23 |

Total Signal | 7.8 $\pm$ 2.0 |

Data | 307 |

AllSB-2JOS
CDF H→WW Opposite sign leptons, Low M_{ll} and Same-Sign Channels

CDF Run II Preliminary \( \int \mathcal{L} = 5.9 \text{ fb}^{-1} \)
\[ M_H = 165 \text{ GeV}/c^2 \]

<table>
<thead>
<tr>
<th>Process</th>
<th>Rate</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t} )</td>
<td>0.55</td>
<td>± 0.10</td>
</tr>
<tr>
<td>( D\bar{Y} )</td>
<td>4.35</td>
<td>± 0.78</td>
</tr>
<tr>
<td>( WW' )</td>
<td>13.8</td>
<td>± 1.3</td>
</tr>
<tr>
<td>( WZ )</td>
<td>0.371</td>
<td>± 0.052</td>
</tr>
<tr>
<td>( ZZ )</td>
<td>0.139</td>
<td>± 0.019</td>
</tr>
<tr>
<td>( W + \text{jets} )</td>
<td>16.2</td>
<td>± 3.0</td>
</tr>
<tr>
<td>( W\gamma )</td>
<td>76.8</td>
<td>± 7.7</td>
</tr>
<tr>
<td>Total Background</td>
<td>112.2</td>
<td>± 8.6</td>
</tr>
<tr>
<td>( gg \rightarrow H )</td>
<td>1.00</td>
<td>± 0.20</td>
</tr>
<tr>
<td>Total Signal</td>
<td>1.00</td>
<td>± 0.20</td>
</tr>
<tr>
<td>Data</td>
<td>112</td>
<td></td>
</tr>
</tbody>
</table>

CDF Run II Preliminary \( \int \mathcal{L} = 5.9 \text{ fb}^{-1} \)
\[ M_H = 165 \text{ GeV}/c^2 \]

<table>
<thead>
<tr>
<th>Process</th>
<th>Rate</th>
<th>Error</th>
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</thead>
<tbody>
<tr>
<td>( t\bar{t} )</td>
<td>0.159</td>
<td>± 0.037</td>
</tr>
<tr>
<td>( D\bar{Y} )</td>
<td>21.0</td>
<td>± 5.6</td>
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<tr>
<td>( WW' )</td>
<td>0.047</td>
<td>± 0.013</td>
</tr>
<tr>
<td>( WZ )</td>
<td>10.4</td>
<td>± 1.4</td>
</tr>
<tr>
<td>( ZZ )</td>
<td>2.07</td>
<td>± 0.28</td>
</tr>
<tr>
<td>( W + \text{jets} )</td>
<td>36</td>
<td>± 14</td>
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<tr>
<td>( W\gamma )</td>
<td>4.89</td>
<td>± 0.78</td>
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<tr>
<td>Total Background</td>
<td>75</td>
<td>± 15</td>
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<tr>
<td>( WH )</td>
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<td>± 0.24</td>
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<tr>
<td>( ZH )</td>
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<td>± 0.28</td>
</tr>
<tr>
<td>Data</td>
<td>74</td>
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</tr>
</tbody>
</table>

CDF Run II Preliminary
\( \int \mathcal{L} = 5.9 \text{ fb}^{-1} \)
\[ M_H = 165 \text{ GeV}/c^2 \]

CDF Run II Preliminary
\( \int \mathcal{L} = 5.9 \text{ fb}^{-1} \)
\[ M_H = 165 \text{ GeV}/c^2 \]

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36
CDF H→WW Trilepton Channels

CDF Run II Preliminary \( \int \mathcal{L} = 5.9 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>Event</th>
<th>( M_H = 165 \text{ GeV}/c^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( tt )</td>
<td>0.37 ± 0.11</td>
</tr>
<tr>
<td>( WZ )</td>
<td>5.35 ± 0.76</td>
</tr>
<tr>
<td>( ZZ )</td>
<td>1.30 ± 0.18</td>
</tr>
<tr>
<td>( W+\text{jets} )</td>
<td>2.92 ± 0.72</td>
</tr>
<tr>
<td>( Z\gamma )</td>
<td>3.13 ± 0.62</td>
</tr>
</tbody>
</table>

Total Background: 13.1 ± 1.5

CDF Run II Preliminary \( \int \mathcal{L} = 5.9 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>Event</th>
<th>( M_H = 165 \text{ GeV}/c^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( tt )</td>
<td>0.067 ± 0.030</td>
</tr>
<tr>
<td>( WZ )</td>
<td>8.5 ± 1.4</td>
</tr>
<tr>
<td>( ZZ )</td>
<td>3.97 ± 0.57</td>
</tr>
<tr>
<td>( W+\text{jets} )</td>
<td>5.1 ± 1.3</td>
</tr>
<tr>
<td>( Z\gamma )</td>
<td>4.14 ± 0.85</td>
</tr>
</tbody>
</table>

Total Background: 21.8 ± 2.7

CDF Run II Preliminary \( \int \mathcal{L} = 5.9 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>Event</th>
<th>( M_H = 165 \text{ GeV}/c^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( WH )</td>
<td>0.0280 ± 0.0046</td>
</tr>
<tr>
<td>( ZH )</td>
<td>0.203 ± 0.032</td>
</tr>
</tbody>
</table>

Total Signal: 0.231 ± 0.035

CDF Run II Preliminary \( \int \mathcal{L} = 5.9 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>Event</th>
<th>( M_H = 165 \text{ GeV}/c^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( WH )</td>
<td>0.0085 ± 0.0017</td>
</tr>
<tr>
<td>( ZH )</td>
<td>0.491 ± 0.072</td>
</tr>
</tbody>
</table>

Total Signal: 0.500 ± 0.073

Data: 11

---

CDF Run II Preliminary \( \int \mathcal{L} = 5.9 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>Event</th>
<th>( M_H = 165 \text{ GeV}/c^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ZH )</td>
<td>4.14 ± 0.85</td>
</tr>
<tr>
<td>( Z\gamma )</td>
<td>3.13 ± 0.62</td>
</tr>
</tbody>
</table>

Tevatron SM Higgs Searches T. Junk ANL 19 Oct 2010
CDF H$\rightarrow$WW Lepton + $\tau_{had}$ Channels (e and $\mu$ Channels)

| Channel                     | CDF Run II Preliminary $|\mathcal{L}| = 5.9$ fb$^{-1}$ | $m_H = 160$ GeV/c$^2$ |
|-----------------------------|------------------------------------|-----------------------|
| dijet, $\gamma$+ jet       | 4 $\pm$ 22                         | 2.1 $\pm$ 0.3        |
| $Z \rightarrow \tau\tau$   | 0.3 $\pm$ 0.2                      | 0.5 $\pm$ 0.3        |
| $Z \rightarrow \ell\ell$   | 7.7 $\pm$ 1.6                      | 41.1 $\pm$ 6.2       |
| W+jets                      | 395 $\pm$ 66                       | 229 $\pm$ 39         |
| $W\gamma$                   | 2.1 $\pm$ 0.3                      | 1.2 $\pm$ 0.2        |
| Diboson (WW, WZ, ZZ)        | 15.2 $\pm$ 2.3                     | 10.1 $\pm$ 1.5       |
| $t\bar{t}$                  | 10.7 $\pm$ 2.6                     | 4.8 $\pm$ 0.9        |
| **Total Background**        | 435 $\pm$ 70                       | 291 $\pm$ 43         |
| $gg \rightarrow H$          | 0.677 $\pm$ 0.085                  | 0.408 $\pm$ 0.052    |
| $WH$                        | 0.160 $\pm$ 0.022                  | 0.099 $\pm$ 0.014    |
| $ZH$                        | 0.104 $\pm$ 0.014                  | 0.063 $\pm$ 0.009    |
| $VBF$                       | 0.059 $\pm$ 0.009                  | 0.036 $\pm$ 0.006    |
| **Total Signal**            | 1.000 $\pm$ 0.089                  | 0.606 $\pm$ 0.055    |
| **Data**                    | 446                                | 295                   |

**e$\tau$ channel**

**$\mu$$\tau$ channel**

![CDF Run II Preliminary $|\mathcal{L}| = 5.9$ fb$^{-1}$, $m_H = 160$ GeV/c$^2$](image1)

![CDF Run II Preliminary $|\mathcal{L}| = 5.9$ fb$^{-1}$, $m_H = 160$ GeV/c$^2$](image2)
Two Techniques for Computing Limits

**CL$_s$ (used by D0)**

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

-2 ln Q = LLR = \text{Signal-}bkg-\text{like}

\[\text{CL}_b = P(-2\ln Q \geq -2\ln Q_{\text{obs}} \mid b \text{ only})\]

Green area = \text{CL}_s+b = \text{CL}_s+b = P(-2\ln Q \geq -2\ln Q_{\text{obs}} \mid s+b)

Yellow area = “1-CL$_b$” = P(-2\ln Q \leq -2\ln Q_{\text{obs}} \mid b \text{ only})

\[\text{CL}_s = \text{CL}_s+b / \text{CL}_b \geq \text{CL}_s+b\]

Exclude at 95% CL if CL$_s$<0.05

Vary \( r \) until CL$_s$=0.05 to get $R_{\text{lim}}$

Expected limits can be computed from the distributions of -2lnQ

**Bayesian (used by CDF)**

\[L'(data \mid R) = \int L(data \mid R, \theta)\pi(\theta)d\theta\]

Using Joel Heinrich’s and Luc Demortier’s “correlated” prior – flat in the accepted signal yield

Example: CDF at 165 GeV

Expected limits are computed with pseudoexperiments
CDF Combined $H \rightarrow WW$ Limits, ICHEP 2010

![Graph showing CDF Run II Preliminary results for $H \rightarrow WW$ limits with 95% C.L. of $\sigma_{SM}$]
CDF’s Low-Mass Searches

Lepton + MET + bb -- Primarily WH→lvbb signal
MET + bb (veto leptons) -- Z→vv, but also WH→lvbb
llbb Primarily ZH→llbb
H→ττ+2 jets WH, ZH, ggH and VBF all included

What’s not included: gg→H→bb: dominant production and decay, but gg→bb is millions of times bigger.

We can see Z→bb in this last channel but the s/b is small and the Z production cross section is about 8000 pb instead of 1 pb
CDF’s Searches for WH $\rightarrow$ lvbb

- Select events with an identified lepton (e, mu, or isolated track), MET, two or three jets, and one or more b-tags
- Divide search channels by b-tag category (one or two tags, loose and tight b-taggers), lepton, and jet categories.
  - Different signal and background contributions,
  - Different s/b (better dijet mass resolution in double-tag events!)
  - Different systematics
- Train separate neural networks/matrix element discriminants in each category

Single b-tag

Tight+Loose b-tag

Two tight b-tags
NN b-jet energy corrections – similar width of $m_{jj}$ for signal, but higher average, so better relative resolution.

Does not sculpt background

3-jet events use matrix-element (+ flavor-separator) discriminants

NN Built out of (example, double-tight tag, two-jet events):
- $m_{jj}$
- $P_T$ Imbalance
- $M_{\text{max}}(l+v+\text{jet})$
- $Qx\eta_{\text{lepton}}$
- Sum $E_T$(loose jets)
- $P_T(W)$
- $H_T$
The Top Two WH Events at $m_H=115$ GeV

This was found as the most Higgs like event at 1.9/1 analysis (event display was blessed).

Our BNN re-finds this event!!

$s/b$ or each of these events is 0.3 to 0.4
CDF’s MET+bb Search

- Events collected with a MET+jets trigger
- MET>50 GeV, 2 or 3 jets, one or two b-tags, lepton veto to be orthogonal to lvbb analysis
- Anti-QCD neural network to target dominant background – dijet events with mismeasured MET (usually MET points along one of the jets, and calorimeter MET and track MET are misaligned if it’s fake)

<table>
<thead>
<tr>
<th>Process</th>
<th>Excl. ST</th>
<th>ST+ST</th>
<th>ST+JP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Pair</td>
<td>381.1 ± 46.4</td>
<td>89.7 ± 13.0</td>
<td>76.7 ± 13.0</td>
</tr>
<tr>
<td>Single Top</td>
<td>136.4 ± 24.5</td>
<td>32.3 ± 6.3</td>
<td>24.6 ± 5.3</td>
</tr>
<tr>
<td>Diboson</td>
<td>106.5 ± 17.3</td>
<td>14.2 ± 2.6</td>
<td>12.4 ± 2.5</td>
</tr>
<tr>
<td>Z+HF</td>
<td>399.7 ± 129.6</td>
<td>32.7 ± 11.1</td>
<td>35.0 ± 12.3</td>
</tr>
<tr>
<td>W+HF</td>
<td>1065.2 ± 356.0</td>
<td>49.7 ± 17.4</td>
<td>68.5 ± 24.9</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>1108.0 ± 113.8</td>
<td>43.5 ± 9.7</td>
<td>120.3 ± 13.3</td>
</tr>
<tr>
<td>Exp. Background</td>
<td>3196.9 ± 501.8</td>
<td>262.2 ± 33.5</td>
<td>337.7 ± 42.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>ST</th>
<th>JP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZH \rightarrow llbb \ (m_H = 115 \text{ GeV})$</td>
<td>3220</td>
<td>237</td>
<td>301</td>
</tr>
<tr>
<td>$WH \rightarrow lvbb \ (m_H = 115 \text{ GeV})$</td>
<td>0.3 ± 0.02</td>
<td>0.2 ± 0.02</td>
<td>0.1 ± 0.02</td>
</tr>
<tr>
<td>$ZH \rightarrow \nu\nu bb \ (m_H = 115 \text{ GeV})$</td>
<td>5.9 ± 0.3</td>
<td>2.8 ± 0.2</td>
<td>2.1 ± 0.3</td>
</tr>
</tbody>
</table>

Tevatron SM Higgs Searches T. Junk ANL 19 Oct 2010
CDF’s llbb Search

- High purity sample of $Z \rightarrow ee$, $Z \rightarrow \mu\mu +$ jets
- Technical challenge to loosen all the lepton ID requirements and calibrate efficiencies and fake rates for loose lepton categories
- Special feature: No real MET in signal events (and most background events). Use MET projections and a neural network to improve $m_{bb}$ resolution
- Low expected signal yield though ($Br(Z \rightarrow ll) \sim 3\%$)

Example yield table:

<table>
<thead>
<tr>
<th></th>
<th>High $S/\sqrt{B}$</th>
<th>Low $S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZH$</td>
<td>0.7 ± 0.1</td>
<td>0.1 ± 0.02</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>9.9 ± 1.5</td>
<td>4.4 ± 0.7</td>
</tr>
<tr>
<td>$WW$</td>
<td>0.02 ± 0.003</td>
<td>0 ± 0.0</td>
</tr>
<tr>
<td>$WZ$</td>
<td>0.1 ± 0.02</td>
<td>0.03 ± 0.004</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>3.6 ± 0.5</td>
<td>0.7 ± 0.1</td>
</tr>
<tr>
<td>$Z \rightarrow ll + b\bar{b}$</td>
<td>22.1 ± 9.2</td>
<td>4.6 ± 1.9</td>
</tr>
<tr>
<td>$Z \rightarrow ll + c\bar{c}$</td>
<td>2.4 ± 1.0</td>
<td>0.5 ± 0.2</td>
</tr>
<tr>
<td>$Z \rightarrow ll + l.f.$</td>
<td>1.2 ± 0.2</td>
<td>0.5 ± 0.1</td>
</tr>
<tr>
<td>fakes</td>
<td>0.9 ± 0.5</td>
<td>2.1 ± 1.0</td>
</tr>
<tr>
<td>Total Bkg</td>
<td>40.3 ± 9.4</td>
<td>12.7 ± 2.3</td>
</tr>
<tr>
<td>Total Data</td>
<td>37</td>
<td>14</td>
</tr>
</tbody>
</table>
Three High s/b Candidates in the llbb Channels

s/b of each of these events is 0.3 to 0.4
Higgs Boson Couplings to Photons

At one-loop, the Higgs boson couples to photons via a loop of charged particles:

If charged scalars exist, they would contribute as well. These diagrams lead to an effective Lagrangian

\[ \mathcal{L}_{h\gamma\gamma}^{\text{eff}} = \frac{g\alpha N_\gamma}{12\pi m_W} h^0 F_{\mu\nu} F^{\mu\nu}, \]

where

\[ N_\gamma = \sum_i N_{ci} e_i^2 F_j(x_i), \quad x_i \equiv \frac{m_i^2}{m_h^2}. \]

In the sum over loop particles $i$ of mass $m_i$, $N_{ci} = 3$ for quarks and 1 for color singlets, $e_i$ is the electric charge in units of $e$ and $F_j(x_i)$ is the loop function corresponding to $i$th particle (with spin $j$). In the limit of $x \gg 1$,

\[ F_j(x) \rightarrow \begin{cases} 
1/4, & j = 0, \\
1, & j = 1/2, \\
-21/4, & j = 1.
\end{cases} \]

H. Haber, HCPSS 2008
A New Diphoton Channel

- Uses triggers based on 2 or more EM clusters. Lower-energy threshold triggers have isolation requirements, higher-energy triggers loosen this.
- Single-photon triggers
  - Photons are required to be central -- $|\eta|<1.04$
  - Isolation required -- < 2 GeV of tracks pointing at a photon candidate and < 2 GeV of non-photon candidate calorimeter energy
CDF Run II Preliminary, \( <L> = 5.6-5.9 \text{ fb}^{-1} \)

- WH+ZH+VBF\( \rightarrow \)jjbb 4.0 \text{ fb}^{-1} \) Obs
- WH+ZH+VBF\( \rightarrow \)jjbb 4.0 \text{ fb}^{-1} \) Exp
- \( \text{H} \rightarrow \tau \tau \) 2.3 \text{ fb}^{-1} \) Obs
- \( \text{H} \rightarrow \tau \tau \) 2.3 \text{ fb}^{-1} \) Exp
- \( \text{ZH} \rightarrow \)llbb 5.7 \text{ fb}^{-1} \) Obs
- \( \text{ZH} \rightarrow \)llbb 5.7 \text{ fb}^{-1} \) Exp
- \( \text{WH} \rightarrow \)Metbb 5.7 \text{ fb}^{-1} \) Obs
- \( \text{WH} \rightarrow \)Metbb 5.7 \text{ fb}^{-1} \) Exp
- \( \text{WH} \rightarrow \)lvbb2j 5.7 \text{ fb}^{-1} \) Obs
- \( \text{WH} \rightarrow \)lvbb2j 5.7 \text{ fb}^{-1} \) Exp
- \( \text{H} \rightarrow \gamma \gamma \) 5.4 \text{ fb}^{-1} \) Obs
- \( \text{H} \rightarrow \gamma \gamma \) 5.4 \text{ fb}^{-1} \) Exp
- \( \text{WH} \rightarrow \)lvbb3j 5.6 \text{ fb}^{-1} \) Obs
- \( \text{WH} \rightarrow \)lvbb3j 5.6 \text{ fb}^{-1} \) Exp
- \( \text{H} \rightarrow \)WW 5.9 \text{ fb}^{-1} \) Obs
- \( \text{H} \rightarrow \)WW 5.9 \text{ fb}^{-1} \) Exp
- Combined Obs
- Combined Exp

Tevatron SM Higgs Searches T. Junk ANL 19 Oct 2010
CDF Run II Preliminary, $\langle L \rangle = 5.6-5.9$ fb$^{-1}$

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

95% CL Limit/SM

$\sqrt{s}$ = 1.96 TeV

$10^0$ $10^1$ $10^2$ $10^3$

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

- SM=1

July 19, 2010
Tevatron SM Higgs Searches T. Junk ANL 19 Oct 2010
What These Look Like for a 5.0σ Observation

CDF Single Top, 3.2 fb⁻¹
Tevatron Correlated Systematic Uncertainties 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)
$\sigma_{\text{WW}} = 12.4 \pm 0.7 \text{ pb}$
$\sigma_{\text{WZ}} = 3.7 \pm 0.2 \text{ pb}$
$\sigma_{\text{ZZ}} = 3.8 \pm 0.2 \text{ pb}$

$\text{ttbar}$ Cross Section: Moch and Uwer, evaluated at $m_t=172.4\pm1.2 \text{ GeV}$ is $\sigma_{\text{tt}}=7.794$ with a 10% syst. assigned
Tevatron Correlated Systematic Uncertainties II

Signal Cross Section uncertainties:
  WH, ZH: ± 5%
  gg→H: ± 23% (Weighted over the jet bins with different uncertainties)
  VBF: ± 10%

These uncertainties are treated like other systematic uncertainties, e.g. acceptance uncertainties.

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

**CDF-D0 Uncorrelated** uncertainties:
  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
Steps Required for Combination

• Histograms and named rate *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 DØ teams each do three combinations, using Bayesian and CL$_s$ techniques.
  - CDF
  - DØ

Tevatron
  Consistency at the better than 5% level required for all combinations at all test masses. *Take the Bayesian limits (a priori, if for no reason than because we always have).*
Looking for a Hint of a Signal

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

Excluded regions:
158 < m_H < 175 GeV
100 < m_H < 109 GeV

Expected Exclusion (if no signal is present):
156 < m_H < 173 GeV
Tevatron Projected Performance

We continue to improve our analyses as well as collect more data.

Multivariate analyses are pretty much at their limit: We now seek more acceptance, looser requirements, new channels...
ATLAS

H → γγ
H → ZZ* → 4l
H → ττ
H → WW → eνμν
• Issues: not all input channels are final and published. low-\(m_{\mu\mu}\), taus and trileptons (new for Moriond 2010). Most low-mass channels are newer and have more data than their last publications.

• Still want to publish the test of \(m_H \sim 2M_W\). So publish three PRL’s, one from CDF, one from D0, and one combining them, for all the OS+SS channels.

• On agreement of CDF and D0, produce a single author list sorted alphabetically. 1042 Authors! 132 Institutions!
Inclusive Search for Standard Model Higgs Boson Production in the \(WW\) Decay Channel Using the CDF II Detector

T. Aaltonen et al. (CDF Collaboration)

Search for Higgs Boson Production in Dilepton and Missing Energy Final States with 5.4 \(fb^{-1}\) of \(pp\) Collisions at \(\sqrt{s} = 1.96\) TeV

V. M. Abazov et al. (D0 Collaboration)

Combination of Tevatron Searches for the Standard Model Higgs Boson in the \(W^+W^-\) Decay Mode

T. Aaltonen et al. (CDF and D0 Collaborations) 1042 Authors!
The February 2010 $H \rightarrow WW$ (well, IIOMET really) Combination PRL

- Events/0.267 vs $\log_{10}(s/b)$
- $m_h = 165$ GeV
- $m_h$ excluded between 162 and 166 GeV
- LLR and L-CL$^s$ plots with observed and expected values.
We made the cover!

And we are the subject of a Viewpoint article by Klaus Mönig

Fourth Generation Analysis Strategy

- Not a straight-up model drawn on the same exclusion curve:
  - $\sigma(gg\rightarrow H)$ is enhanced by a factor of 9 ($m_H=100$ GeV) to 7.5 ($m_H=300$ GeV) but WH, ZH, and VBF remain unchanged
  - SM combination assumes SM mixture of $gg\rightarrow H$, WH, ZH, and VBF

- Strategy:
  - Remove WH, ZH, and VBF signals, and retrain discriminants just for $gg\rightarrow H$
  - Extend mass range $110<m_H<260$ GeV (up to 300 GeV coming soon)
  - Compute $\sigma(gg\rightarrow H)$ assuming enhancement factor from Tait, Plehn, Kribs and Spannowsky’s HDECAY. Note: 2-loop EW piece does not get enhanced!
    - But the interference term does (but by only one power).
  - Waiting for a full NNLL calculation, but private communications indicate we’re very close with this prescription.
  - Set limits on $\sigma(gg\rightarrow H) \times \text{Br}(H\rightarrow WW)$. Draw theory curves on top
  - Also produce a mass limit assuming theory and uncertainties treated the same way as for the SM.

- Something to be careful about at high $m_H$: $\Delta\Phi_{ll}$ no longer peaks at low values for the signal. W’s are boosted!
Fourth Generations Possible – Affects the Precision EW Constraint on $m_H$

Four Generations and Higgs Physics
Kribs, Tait, Spannowsky, Plehn
Higgs Boson Decay Branching Fractions and Scenarios

ggH coupling is enhanced, so \( \text{Br}(H \rightarrow gg) \) is enhanced.

SM (Spira)

Two Scenarios: “Infinite Mass:” \( M(f_4) = 1 \text{ TeV} \),

Low-Mass: \( M(b_4) = 128 \text{ GeV}, M(t_4) = 256 \text{ GeV}, 
M(l_4) = 100 \text{ GeV}, M(v_4) = 80 \text{ GeV} \)

4G (Kribs, Tait, Plehn, Spannowsky)
Candidate Summaries in the gg→H Searches, Summed over CDF+D0, all Channels

Bins sorted by s/b, and summed over all channels.
Signal normalized to the infinite-mass scenario

Testing the Fourth-Generation “infinite-mass” scenario at $m_H=200$ GeV
Background model has been fit to the data and subtracted
Error on data – background is \(\sqrt{\text{background}}\)
Blue histogram is the post-fit uncertainty on the background.
Test of the Fourth Generation Hypothesis with $m_H$

CDF+D0 Run II Preliminary
$L = 4.8 - 5.4 \, fb^{-1}$

$130 < m_H < 210 \, GeV$ (approx.)
Excluded assuming a 4$^{th}$ Generation

4G(low-mass)

4G(infinite-mass) = 1

Expected
Observed
±1 s.d. Expected
±2 s.d. Expected

Multivariate Analyses and Mass Measurement

$$\sigma(\text{WW}+\text{WZ}) = 16.5 \pm 3.2 \text{ pb}$$

CDF

$$\sigma(\text{WW}+\text{WZ}) = 18.1 \pm 4.1 \text{ pb}$$

No attempt at measuring the mass, but mass peak now visible.
Leveraging our Rate Measurements to Measure the Higgs Boson Mass

Assuming SM cross sections and branching fractions, measured rates are strong functions of $m_H$. Example at $m_H=115$ GeV, assuming $+3$ sigma excess, and a median outcome in both the $b\bar{b},\tau\tau$ channels and the $WW$ channels:

Tau channels can contribute here, even with less precise $m_{rec}$ than the $b\bar{b}$ channels
What this looks like at all $m_H$, assuming getting the median SM outcome and have a +3 sigma excess.

Assumes: Same uncertainty on cross section times b.r. for equal lumi and in $b\bar{b}+\tau\tau$ and WW channels.
Stirring it All Together – The LLR Test

Assuming observed and expected +3 sigma excess, and median outcome. Resolution from:

\[-2 \Delta \text{LLR} = \Delta \chi^2 = 1\]

Resolution at 115 GeV: ±5 GeV
Resolution at 135 GeV: ~±10 GeV
• The Tevatron is working VERY WELL! We congratulate the Beams Division for their achievements.

• CDF and D0 have vigorous Higgs boson search efforts

• CDF and D0 together exclude $m_H$ between 158 and 175 GeV assuming the SM. And we expected to do that! (assuming a Higgs boson is truly not there).

• CDF Sensitivity alone is at the SM level at $m_H$=165 GeV

• CDF and D0 together exclude $m_H$ between 130 and 210 GeV (approx) assuming a fourth generation of heavy fermions exists

• CDF and D0 hope to accumulate 10 to 12 $fb^{-1}$ of data by the end of Run II. Possible run beyond 2011 would raise this number.
Backup Material
Parton Luminosities – Comparing 14 TeV LHC to 10 and 7 TeV LHC, and the Tevatron

**Tevatron**: 10 fb\(^{-1}\) analyzable/exp at 1.96 TeV by end 2011. Asking for three more years.

**LHC**: 1 fb\(^{-1}\) per exp by end 2011. Much more data and energy later.
Different PDF sets

- **MSTW08** – fit all previous types of data. Most up-to-date Tevatron jet data. Not most recent HERA combination of data. PDFs at LO, NLO and NNLO.

- **CTEQ6.6** – very similar. Not quite as up-to-date on Tevatron data. PDFs at NLO. New – CT10 include HERA combination and more Tevatron data. Little changes.

- **NNPDF2.0** – include all except HERA jet data (not strong constraint) and heavy flavour structure functions. Include HERA combined data. PDFs at NLO.

- **HERAPDF1.0** – based entirely on HERA inclusive structure functions, neutral and charged current. Use combined data. PDFs at LO, NLO and now NNLO.

- **ABKM09** – fit to DIS and fixed target Drell-Yan data. PDFs at NLO and NNLO.

- **GJR08** – fit to DIS, fixed target Drell-Yan and Tevatron jet data. PDFs at NLO and NNLO.

Use of HERA combined data instead of original data slight increase in quarks at low \( x \) (depending on procedure).
Tevatron Run II Preliminary, $L=2.0-5.4 \text{ fb}^{-1}$

- **LEP Exclusion**
- **Tevatron Exclusion**

- Dotted line: Expected
- Solid line: Observed
- Green area: ±1σ Expected
- Yellow area: ±2σ Expected

95% CL Limit/SM

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

- SM=1

November 2009 Combination (Low and High-mass) for HCP 2009

does not include new WW trilepton or tau channels, CDF lumi=4.8 fb^{-1}

Tevatron SM Higgs Searches T. Junk ANL 19 Oct 2010
Studies of Injecting a Signal at $m_H=115$ GeV

- $lvbb$, MET$bb$, and $llbb$ channels included
- Inject SM*$1.0$ signal at $m_H=115$ GeV on top of SM backgrounds, and generate pseudoexperiments with that.
- Analyze 115 signal+background pseudoexperiments at other test masses – 100 GeV to 150 GeV
- Find the median expected limit assuming signal is there (compute it just as you would without the signal) and compare with the distribution of limits assuming the signal is completely absent.
Comparing $H \rightarrow \gamma \gamma$ with $gg \rightarrow H$ coupling shifts

Coulomb singularity not present in $ggH$ coupling

Moderated by $\Gamma_W$ and $\Gamma_Z$

Passarino, Zurich 2009
Comparing Pythia Differential Distributions to NLO and Resummed Predictions

**Figure 1:** On the left figure, we show the normalized transverse momentum distributions for $m_H = 160\text{ GeV}$ and $\mu = \mu_R = \mu_F = m_H$ using NNLO fixed-order perturbation theory and the resummed calculation of Ref. [56]. On the right figure, the same distribution is shown for MC@NLO, PYTHIA8, and the calculation of Ref. [56].

Anastasiou, Dissertori, Grazzini, Stockli, and Webber 2009
**Cross Sections and Branching Fractions used for ICHEP 2010**

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ggH: Grazzini and de Florian; Anastasiou, Boughezal, Petriello

WH, ZH: Baglio and Djouadi (June 2010, update in hep-ph Sep. 2010 came too late, even though we knew about it a few weeks before ICHEP by e-mail)

VBF: MCFM

Branching Fractions: Spira’s HDECAY v.3.53 (April 2010)