Tevatron Run II

- $pp\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV (1.8 TeV in Run I).
- Run II:
  - Summer 2001 - Autumn 2011.
- Collisions at world highest energy until Nov 2009.
  - Energy frontier for \(\sim\) 25 years!!
- Two multi-purpose detectors (CDF and D0) for wide range of physics studies.
- Delivered: 12 fb\(^{-1}\).
  - Recorded by CDF: 10 fb\(^{-1}\).
  - Recorded by D0: 10 fb\(^{-1}\).
CDF and D0 Detectors

- Both are multipurpose detectors:
  - Top/EWK measurements, Searches for Higgs and New Phenomena, and B physics.
- Precision tracking with Silicon in 1.5 (CDF)/1.8 T (D0) Solenoid field.
- EM/Had calorimeters for e/γ/jet measurement.
- Outer muon chambers.
Constraint on Higgs Mass

- Mass of W Boson (World Average):
  - Before Tevatron Run II:
    \[ m_W = 80.426 \pm 0.034 \text{ GeV}/c^2 \]
  - With Tevatron Run II results:
    \[ m_W = 80.385 \pm 0.015 \text{ GeV}/c^2 \]

- Mass of Top Quark (World Average):
  - Tevatron Run I result:
    \[ m_{top} = 178.0 \pm 4.3 \text{ GeV}/c^2 \]
  - With Tevatron Run II results:
    \[ m_{top} = 173.2 \pm 0.9 \text{ GeV}/c^2 \]

\[ M_{higgs} < 152 \text{ GeV}/c^2 \text{ (95\% CL)} \]

\[ \text{.... was } M_{higgs} < 251 \text{ GeV}/c^2 \text{ (95\% CL) in Spring 2004.} \]
SM Higgs Properties at Tevatron

- $m_H < 135$ GeV (low mass):
  - $gg \rightarrow H \rightarrow bb$ is difficult to see.
  - Look for WH/ZH with leptonic vector boson decays.

- $m_H > 135$ GeV (high mass):
  - Easiest to look for $H \rightarrow WW \rightarrow l\ell l\nu$. 

\[ \text{Diagram showing SM Higgs production and decay channels.} \]
### CDF and D0 analyses

<table>
<thead>
<tr>
<th>Channel</th>
<th>CDF Luminosity $\text{fb}^{-1}$</th>
<th>D0 Luminosity $\text{fb}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WH \rightarrow lvbb$</td>
<td>9.45</td>
<td>9.7</td>
</tr>
<tr>
<td>$ZH \rightarrow llbb$</td>
<td>9.45</td>
<td>9.7</td>
</tr>
<tr>
<td>$ZH \rightarrow vvbb$</td>
<td>9.45</td>
<td>9.5</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>8.3</td>
<td>4.3-6.2</td>
</tr>
<tr>
<td>$WH \rightarrow l\nu\tau\tau / ZH \rightarrow ll\tau\tau$</td>
<td>6.2</td>
<td>7.0</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>10.0</td>
<td>9.7</td>
</tr>
<tr>
<td>$VH \rightarrow jjbb$</td>
<td>9.45</td>
<td></td>
</tr>
<tr>
<td>$ttH \rightarrow WWbwbwb$</td>
<td>9.45</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow \nu\nu\nu\nu$</td>
<td>9.7</td>
<td>8.6-9.7</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow l\nu\tau\nu$</td>
<td>9.7</td>
<td>7.3</td>
</tr>
<tr>
<td>$VH \rightarrow VWW \rightarrow lll + X$</td>
<td>9.7</td>
<td>9.7</td>
</tr>
<tr>
<td>$VH \rightarrow VWW \rightarrow l^\pm l^\pm + X$</td>
<td>9.7</td>
<td>9.7</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow llll$</td>
<td>9.7</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow lvjj$</td>
<td>5.4</td>
<td></td>
</tr>
</tbody>
</table>
General Strategy

• Utilize Multivariate Algorithms (MVA) for better S/B separation.
  – Neural Net, Boosted Decision Tree, Matrix Element, etc.
  – Some analyses use MVA output into another MVA.

• The main channels analyzed the full dataset in Winter 2012.
  – Analysis of events through different triggers.

• Improved $b$-jet energy scale measurement (low mass analyses)
  – $b$-jet energy correction based on NN at CDF.

• Improved $b$-tagging (low mass analyses)
  – Algorithms based on MVA.

• Divide analysis sample into high/low purity subsamples.
  – Subdivision due to lepton and $b$-tag quality.
Improved $b$-tagging

CDF and D0 combine information of secondary vertex and tracks within jet cone by MVA (NN and BDT).

<table>
<thead>
<tr>
<th>Light Flavor Eff.</th>
<th>HOBIT Eff.</th>
<th>SecVtx Eff. (old tagger)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>54%</td>
<td>39%</td>
</tr>
<tr>
<td>2%</td>
<td>59%</td>
<td>47%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Light Flavor Eff.</th>
<th>Lb Eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5%</td>
<td>50%</td>
</tr>
<tr>
<td>4.5%</td>
<td>70%</td>
</tr>
</tbody>
</table>
CDF: $ZH \rightarrow l^+ l^- b \bar{b}$ Channel (1)

- Event Selection:
  - $e^+ e^-$ or $\mu^+ \mu^-$ pair within Z mass window.
  - 2 or 3 jets with 1 or 2 $b$-tagged (4 tag categories).

- Train NN for different background.
CDF: $ZH \rightarrow l^+ l^- b \bar{b}$ Channel (2)

Final Discriminant = separate Signal from all Bkgd.
CDF: $ZH \rightarrow l^+ l^- b\bar{b}$ Channel (3)

CDF Run II Preliminary 9.45/fb
CDF: $ZH \rightarrow l^+l^-b\bar{b}$ Channel (4)

Limit for $M_H = 125$ GeV/c$^2$:

Exp: $3.6 \times \sigma_{SM}$

Obs: $7.2 \times \sigma_{SM}$
D0: $H \rightarrow W^+ W^- \rightarrow l^+ l^- + MET$ Channel (1)

- **Event Selection:**
  - $e^+ e^-, \mu^+ \mu^-$ or $e^\pm \mu^\mp$ pair within $M_{ll} > 15$ GeV.
  - BDT to reject $Z/\gamma^* \rightarrow ll$ in $e^+ e^-, \mu^+ \mu^-$ events.
  - Cut on $M_T(l, MET)$ to reject $Z/\gamma^*$ and multijet for $e^\pm \mu^\mp$ events.
  - Analyze 0, 1, ≥2 jet bins.
- Train a final BDT discriminant against all background.
- $gg \rightarrow H, WH, ZH, VBF$ are considered as signal.
  - Different composition of signal and background in different jet multiplicity.
D0: $H \rightarrow W^+W^- \rightarrow l^+l^- + MET$ Channel (2)

Distributions of the Final discriminant:
D0: $H \to W^+W^- \to l^+l^- + MET$ Channel (3)

Limit for $M_H = 125$ GeV/c$^2$:
- Exp: $3.14 \times \sigma_{SM}$
- Obs: $3.50 \times \sigma_{SM}$

Competitive with each individual $H \to bb$ channel.
CDF and D0: Combined Limit

CDF excludes (95% C.L.):
148.8 < m_H < 175.2 GeV/c^2

D0 excludes (95% C.L.):
159 < m_H < 166 GeV/c^2
CDF+D0 Combined Limit

Expected exclusion: 100<m_H<119, 141<m_H<184 GeV/c^2
Observed exclusion: 100<m_H<106, 147<m_H<179 GeV/c^2

What’s this excess?
History of Analysis Improvement

- Tevatron analyses have been constantly improved.
  - Improvement far better than by the increase of dataset!!
Distribution of the Candidate Events

Candidate events in the combined 16 analyses (≈90 orthogonal subchannels):

Tevatron Run II Preliminary, $L \leq 10 \text{ fb}^{-1}$

$m_h = 125 \text{ GeV/c}^2$

Data - Background

Tevatron Run II Preliminary

Data - Background

SM Higgs Signal

±1 s.d. on Background

February 27, 2012

$m_h = 125 \text{ GeV/c}^2$
P-value of the Tevatron Combination

Tevatron RunII Preliminary
SM Higgs, $L_{\text{int}} \leq 10.0 \text{ fb}^{-1}$

February 2012
Signal Cross Section Best Fit

- Assuming the SM Higgs branching ratio.

- If real, excess around 115-135 GeV is consistent with the Standard Model.
### Summary of Significance

<table>
<thead>
<tr>
<th></th>
<th>Excess Region</th>
<th>Local significance</th>
<th>Global significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF $H \rightarrow bb$</td>
<td>120-135 GeV/c^2</td>
<td>2.9$\sigma$</td>
<td>2.7$\sigma$</td>
</tr>
<tr>
<td>D0 $H \rightarrow bb$</td>
<td>120-125 GeV/c^2</td>
<td>$\sim$1$\sigma$</td>
<td></td>
</tr>
<tr>
<td>Tevatron $H \rightarrow bb$</td>
<td>120-135 GeV/c^2</td>
<td>2.8$\sigma$</td>
<td>2.6$\sigma$</td>
</tr>
<tr>
<td>CDF $H \rightarrow WW$</td>
<td>-</td>
<td>$&lt;1\sigma$</td>
<td></td>
</tr>
<tr>
<td>D0 $H \rightarrow WW$</td>
<td>130-140 GeV/c^2</td>
<td>1.5$\sigma$</td>
<td></td>
</tr>
<tr>
<td>Tevatron $H \rightarrow WW$</td>
<td>130-140 GeV/c^2</td>
<td>$\sim$1$\sigma$</td>
<td></td>
</tr>
<tr>
<td>CDF all chan.</td>
<td>120 GeV/c^2</td>
<td>2.6$\sigma$</td>
<td>2.1$\sigma$</td>
</tr>
<tr>
<td>D0 all chan.</td>
<td>130-135 GeV/c^2</td>
<td>2.1$\sigma$</td>
<td>1.5$\sigma$</td>
</tr>
<tr>
<td>Tevatron all chan.</td>
<td>120-135 GeV/c^2</td>
<td>2.7$\sigma$</td>
<td>2.2$\sigma$</td>
</tr>
</tbody>
</table>

$H \rightarrow bb$ mode drives the Tevatron searches around $m_H \sim 125$ GeV/c^2. 
$\rightarrow$ Complementary to LHC. 
LHC searches are dominated by $H \rightarrow \gamma\gamma, WW, ZZ$. 
Summary

• Both CDF and D0 updated the main analysis channels with full dataset in Winter 2012.
• Tevatron combination now excludes:
  \[ 100 < m_H < 106, \ 147 < m_H < 179 \ \text{GeV}/c^2 \]
  (Expected exclusion: \[ 100 < m_H < 119, \ 141 < m_H < 184 \ \text{GeV}/c^2 \])
• Excess in \[ 110 < m_H < 140 \ \text{GeV}/c^2 \] region.
  – Global significance of \( 2.2 \sigma \) with all analyses combined.
  – Global significance of \( 2.6 \sigma \) with \( H \rightarrow bb \) analyses.
• Summer 2012 combination will include:
  – D0: improvement on \( b \)-tag, \( b \)-jet energy scale and MVA techniques in the main channels.
  – CDF: \( ZH \rightarrow MET+bb \) will update with improved \( b \)-tag.
  – Updates from other channels as well.
BACKUP
Constraints on Higgs Mass (1)

- Mass of W Boson (World Average):
  - Before Tevatron Run II:
    \[ m_W = 80.426 \pm 0.034 \text{ GeV/c}^2 \]
  - With Tevatron Run II results:
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- Mass of Top Quark (World Average):
  - Tevatron Run I result:
    \[ m_{\text{top}} = 178.0 \pm 4.3 \text{ GeV/c}^2 \]
  - With Tevatron Run II results:
    \[ m_{\text{top}} = 173.2 \pm 0.9 \text{ GeV/c}^2 \]
Constraint on Higgs Mass (2)

\[ M_{\text{higgs}} < 152 \text{ GeV}/c^2 \ (95\% \ CL) \ . \]

...was \[ M_{\text{higgs}} < 251 \text{ GeV}/c^2 \ (95\% \ CL) \] in Spring 2004.
CDF and D0 analyses

**TABLE I.** Luminosity, explored mass range and references for the different processes and final states ($\ell = c$ or $\mu$) for the CDF analyses. The generic labels “$2x^-$”, “$3x^-$”, and “$4x^-$” refer to separations based on lepton categories.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity ($fb^{-1}$)</th>
<th>$m_H$ range (GeV/c$^2$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH $\rightarrow \ell\nu\bar{b}b$ 2-jet channels</td>
<td>4x(TT,Tb,Tb,Lb,Lb,Lo,Lo)</td>
<td>9.45</td>
<td>100-150</td>
</tr>
<tr>
<td>WH $\rightarrow \ell\nu\bar{b}b$ 3-jet channels</td>
<td>3x(TT,Tb)</td>
<td>9.45</td>
<td>100-150</td>
</tr>
<tr>
<td>ZH $\rightarrow \nu\nu\bar{b}b$ (SS,SSJ,JS)</td>
<td>9.45</td>
<td>100-150</td>
<td>[18]</td>
</tr>
<tr>
<td>ZH $\rightarrow \ell^+\ell^-\bar{b}b$ 2-jet channels</td>
<td>2x(TT,Tb,Tb,Lb)</td>
<td>9.45</td>
<td>100-150</td>
</tr>
<tr>
<td>ZH $\rightarrow \ell^+\ell^-\bar{b}b$ 3-jet channels</td>
<td>2x(TT,Tb,Tb,Lb)</td>
<td>9.45</td>
<td>100-150</td>
</tr>
<tr>
<td>H $\rightarrow W^+W^-$</td>
<td>2x(0 jets,1 jet)</td>
<td>9.7</td>
<td>110-200</td>
</tr>
<tr>
<td>$I$ $\rightarrow W^+W^-$</td>
<td>(c-$\tau_{had}$)+(c-$\tau_{had}$)</td>
<td>9.7</td>
<td>130-200</td>
</tr>
<tr>
<td>WH $\rightarrow WW^+W^-$</td>
<td>(same-sign leptons)+(tri-leptons)</td>
<td>9.7</td>
<td>110-200</td>
</tr>
<tr>
<td>WH $\rightarrow WW^+W^-$</td>
<td>tri-leptons with 1 $\tau_{had}$</td>
<td>9.7</td>
<td>110-200</td>
</tr>
<tr>
<td>ZH $\rightarrow ZW^+W^-$</td>
<td>tri-leptons with 1 jet+(tri-leptons with 2 or more jets)</td>
<td>9.7</td>
<td>110-200</td>
</tr>
<tr>
<td>H $\rightarrow ZZ$</td>
<td>(3 leptons)</td>
<td>9.7</td>
<td>120-200</td>
</tr>
<tr>
<td>$H$ $\rightarrow X$</td>
<td>(1 jet)</td>
<td>8.3</td>
<td>100-150</td>
</tr>
<tr>
<td>WH $\rightarrow \ell^+\ell^-\ell^-\ell^-/ZH$</td>
<td>$\ell^+\ell^-\ell^-\ell^-\bar{\tau}_{had}$</td>
<td>6.2</td>
<td>100-150</td>
</tr>
<tr>
<td>WH $\rightarrow \ell^+\ell^-\ell^-/ZH$</td>
<td>$\ell^+\ell^-\ell^-\bar{\tau}_{had}$</td>
<td>6.2</td>
<td>100-150</td>
</tr>
<tr>
<td>WH $\rightarrow \ell^+\ell^-\ell^-/ZH$</td>
<td>$\ell^+\ell^-\ell^-\bar{\tau}_{had}$</td>
<td>6.2</td>
<td>100-150</td>
</tr>
<tr>
<td>ZH $\rightarrow \ell^+\ell^-\ell^-\ell^-$</td>
<td>four leptons including $\tau_{had}$ candidates</td>
<td>6.2</td>
<td>100-150</td>
</tr>
<tr>
<td>WH $\rightarrow ZH$</td>
<td>(SS,SSJ)</td>
<td>9.45</td>
<td>120-200</td>
</tr>
<tr>
<td>WH $\rightarrow j\bar{b}b$ (CC,CP,CC,Conv,PC,Conv)</td>
<td>10.0</td>
<td>100-150</td>
<td>[26]</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>WW$b^b$ (lepton)</td>
<td>9.45</td>
<td>100-150</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>WW$b^b$ (no lepton)</td>
<td>5.7</td>
<td>100-150</td>
</tr>
</tbody>
</table>

**TABLE II.** Luminosity, explored mass range and references for the different processes and final states ($\ell = c$, $\mu$) for the D0 analyses.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity ($fb^{-1}$)</th>
<th>$m_H$ range (GeV/c$^2$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH $\rightarrow \ell\nu\bar{b}b$ (TST,LDT,LDT)</td>
<td>(2,3 jet)</td>
<td>9.7</td>
<td>100-150</td>
</tr>
<tr>
<td>ZH $\rightarrow \nu\nu\bar{b}b$ (MS,TST)</td>
<td>9.5</td>
<td>100-150</td>
<td>[30]</td>
</tr>
<tr>
<td>ZH $\rightarrow \ell^+\ell^-\bar{b}b$ (TST,TLDT)</td>
<td>(c,c,c,c,c,c,c,c,c,c)</td>
<td>9.7</td>
<td>100-150</td>
</tr>
<tr>
<td>$H+X$ $\rightarrow \ell^+\tau_{had}$</td>
<td>4.3-6.2</td>
<td>105-200</td>
<td>[32]</td>
</tr>
<tr>
<td>$VH$ $\rightarrow e^+\mu^-+X$</td>
<td>9.7</td>
<td>115-200</td>
<td>[33]</td>
</tr>
<tr>
<td>$H$ $\rightarrow W^+W^-$</td>
<td>$\ell^\pm\nu\bar{\nu}$</td>
<td>(0,1,2+ jet)</td>
<td>8.6-9.7</td>
</tr>
<tr>
<td>$H$ $\rightarrow W^+W^-$</td>
<td>$\mu\tau_{had}$</td>
<td>7.3</td>
<td>115-200</td>
</tr>
<tr>
<td>$H$ $\rightarrow W^+W^-$</td>
<td>$\nu\bar{\nu}$</td>
<td>5.4</td>
<td>135-200</td>
</tr>
<tr>
<td>$VH$ $\rightarrow \ell\ell+X$</td>
<td>9.7</td>
<td>100-150</td>
<td>[36]</td>
</tr>
<tr>
<td>$VH$ $\rightarrow \tau\tau+X$</td>
<td>7.0</td>
<td>115-200</td>
<td>[37]</td>
</tr>
<tr>
<td>$H$ $\rightarrow \gamma\gamma$</td>
<td>9.7</td>
<td>100-150</td>
<td>[38]</td>
</tr>
</tbody>
</table>
Sensitivity of Analysis Channels (CDF)
Neural Net $b$-jet energy correction (CDF)

- A neural net was trained using $b$-jets in $H \rightarrow bb$ Monte Carlo events to return a scale factor for jet energy.
CDF: ZH→llbb

- Electron channels
- Here we observe a significant change

---

**Winter 2012**

**Summer 2011**
Examine top 20 events in both channels based on S/B of the discriminant bin in which it’s located.

The electron channel contains 12 new candidates within this high score region, while muon channel has 5.
To study the effect of high S/B events on our observed limits, we remove our best new and best two new events from the $e^+e^-$ channel and re-run the limits.

Gives one sigma level changes in the limits at 120 GeV/c$^2$
D0: $H \rightarrow l^+ l^- + MET$ Channel
LLR of Tevatron Combination

\[ LLR = -2 \ln \frac{p(data; s + b)}{p(data; b)} \]
With 125 GeV signal, we expect a broad excess over the entire mass region.

Consistent with SM signal plus background hypothesis over Higgs mass range from 110 to 140 GeV/c^2
$H \rightarrow bb$ Channel by Channel (CDF,D0)
By Decay Mode (CDF, D0)

CDF Run II Preliminary $H \rightarrow \text{bb}$ $L = 9.5 \text{ fb}^{-1}$

CDF Run II Preliminary $H \rightarrow \text{WW}$ $L = 9.7 \text{ fb}^{-1}$

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

$H \rightarrow \text{b}\overline{\text{b}}$ Combination

$H \rightarrow \text{WW}$ Combination
CDF H→WW OS channels

- Channels with oppositely charged dileptons.

0jet: 1jet 2jet
$H \rightarrow bb$ (CDF+D0)
CDF H$\rightarrow$bb  Signal Injection study

Because our neural network discriminants are optimized for separation of signal and background rather than mass reconstruction, we expect to observe (in the presence signal) higher than expected observed limits over a broad mass range.
$H \rightarrow WW$ (CDF+D0)
CDF combination plots

CDF Run II Preliminary
SM Higgs, $L_{\text{int}} \leq 10.0 \text{ fb}^{-1}$

February 2012

CDF Run II Preliminary, $L \leq 10 \text{ fb}^{-1}$

CDF Run II Preliminary
$L \leq 10 \text{ fb}^{-1}$

February 27, 2012
D0 combination plots

D0 Preliminary, L_{int} \leq 9.7 fb^{-1}

SM Higgs Combination

1-CL_{b} Observed
1-CL_{b} Expected
Expected \pm 1 s.d.
Expected \pm 2 s.d.

Higgs Boson Mass (GeV/c^2)

Best Fit \sigma/\sigma_{SM}

D0 Preliminary, L_{int} \leq 9.7 fb^{-1}

SM Higgs Combination

Best Fit
\pm 1 s.d.

Higgs Boson Mass (GeV/c^2)