Higgs Searches at the Tevatron

Bob Hirosky
University of Virginia
Tevatron Accelerator and Experiments

Tevatron Run 2 data collection completed Sept. 30 2011
~ 10 year program of data collection at highest pp collisions energies

~33 billion events recorded (D0) + similar for CDF
Enormous debt of gratitude to Fermilab Accelerator Division for outstanding performance

Run II Integrated Luminosity

Full data sets > 10 fb-1
For both experiments
Good accelerator performance introduces its own challenges

The good: >10 fb$^{-1}$ recorded per experiment
~ 60 pb$^{-1}$/week

The challenge: Peak luminosity to up 4x10$^{32}$ cm$^{-1}$s$^{-1}$

Brings all the expected (and often unexpected) complexities from multiple pp interactions / beam crossing.

Increasing challenges in:
- Triggers
- Object reconstruction and ID
- Efficiency measurements
- MC modeling
- ...

![Instantaneous luminosity](image)
CDF and DØ Detectors

Large, multipurpose detectors

* Tracking
* Calorimetry
* Muon detection
* Missing ET → infer ν's

Large tracking volume

Hermetic calorimetry, μ coverage
Predictions for Higgs Mechanism

We have a theory that has captured the imaginations and interests of physicists and the general public.

Getting a handle on the origin of (any) elementary particle masses, is an exciting prospect for physics!
Predictions for Higgs Mechanism

We have a theory that has captured the imaginations and interests of physicists and the general public.

Getting a handle on the origin of (any) elementary particle masses, is an exciting prospect for physics!

Very testable theory
Leading contributions to

Higgs Boson Production Rates

Multiple channels contribute in region of interest
Major challenge of
Standard Model Physics Processes

Tevatron Run II, $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV

- Jets
- Heavy Flavor
- $W$, $Z$
- $W\gamma$, $Z\gamma$
- $WW$
- $tt$
- $WZ$
- Single Top
- $ZZ$
- Higgs

- $\sim 9$ orders of magnitude!
- New physics?

strong and EW processes measured over wide 'dynamic range' in SM
Major challenge of

Standard Model Physics Processes

Tevatron Run II, $\sqrt{s} = 1.96$ TeV

Production Rate

- Jets
- Heavy Flavor
- $W$, $Z$
- $W\gamma$, $Z\gamma$
- $WW$, $tt$, $WZ$
- Single Top
- $ZZ$
- Higgs

- CDF Preliminary
- CDF Published
- Theory

$\sim 9$ orders of magnitude!

strong and EW processes measured over wide 'dynamic range' in SM

New physics?
Primary Search Channels

**Low Mass**
- qq → WH, ZH
  - Decay: H → bb
- Favored modes: bb+lv, bb+vv, bb+ll
- Detection: lepton acceptance, b-tagging, dijet resol.

**High Mass**
- gg → H
  - Decay: H → WW
- Favored modes: lv+lv
- Detection: Missing $E_T$, angular correlations

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Primary Search Channels

**Low Mass**

- qq $\rightarrow$ WH, ZH

- **Decay:** $H \rightarrow bb$

- **Favored modes:** bb+lv, bb+vv, bb+ll

- **Detection:** lepton acceptance, b-tagging, dijet resol.

**High Mass**

- gg $\rightarrow$ H

- **Decay:** $H \rightarrow WW$

- **Detection:** angular correlations, Missing $E_T$
Primary Search Channels

<table>
<thead>
<tr>
<th>Low Mass</th>
<th>High Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$qq \rightarrow WH,ZH$</td>
<td>$gg \rightarrow H$</td>
</tr>
<tr>
<td>$\downarrow$</td>
<td>$\downarrow$</td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td>$H \rightarrow WW$</td>
</tr>
</tbody>
</table>

Decay:

<table>
<thead>
<tr>
<th>Favored modes:</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$bb+\nu\nu$</td>
<td>$\nu\nu$</td>
<td></td>
</tr>
<tr>
<td>$bb+\nu\nu$</td>
<td>$\nu\nu$</td>
<td></td>
</tr>
<tr>
<td>$bb+ll$</td>
<td>$ll$</td>
<td></td>
</tr>
</tbody>
</table>

Detection:

- lepton acceptance
- b-tagging
- dijet resol.
- angular correlations
- Missing $E_T$

Actively pursuing improvements in all non-negligible channels to complete results with full 10 fb$^{-1}$ data set.
Background Reduction

Uncertainties on background are larger than expected signal

- Need to go beyond simple counting experiment in searches
- Use shape information (kinematic and topological variables)
- Construct multivariate discriminants to improve S/B
- Improve resolutions, purity – while preserving acceptance
Background Reduction

Uncertainties on background are larger than expected signal

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Dependent on **modeling of input variables**

- Validate input variables and MVA output with data in control regions and signal regions
- Validate robustness of techniques and background model by successful measurements of other processes in similar final states

Examples: Single top discovery, diboson production measurements
Background Modeling

Depend on Monte Carlo event generators to model W/Z+jets

Perform detailed studies to understand quality of modeling

Avoid washing out a signal or creating false positives

Cross check against dedicated measurements with known signals

See talk by D. Price
b-tagging

S. Desai  FNAL W&C 03/12
Extend to “event-level” btagging

Consider sum of btag outputs for bb signals
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b-tagging

CDF Higgs Optimized b Identification Tagger (HOBIT)

25-input vars, trained for $H \rightarrow b\bar{b}$

See talk by M. Kirby

<table>
<thead>
<tr>
<th>mistag rate</th>
<th>SecVtx efficiency</th>
<th>HOBIT efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>~1%</td>
<td>39%</td>
<td>54%</td>
</tr>
<tr>
<td>~2%</td>
<td>47%</td>
<td>59%</td>
</tr>
</tbody>
</table>

M. Stancari FNAL W&C 03/12
**HOBIT WH-\to{l}\nu b**

<table>
<thead>
<tr>
<th>OLD – Multiple Taggers</th>
<th>Tagging Category</th>
<th>S/\sqrt{B}</th>
</tr>
</thead>
<tbody>
<tr>
<td>SecVtx+SecVtx</td>
<td></td>
<td>0.228</td>
</tr>
<tr>
<td>SecVtx+JetProb</td>
<td></td>
<td>0.160</td>
</tr>
<tr>
<td>SecVtx+Roma</td>
<td></td>
<td>0.103</td>
</tr>
<tr>
<td>Single SecVtx</td>
<td></td>
<td>0.146</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td></td>
<td><strong>0.331</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>New Hobbit</th>
<th>Tagging Category</th>
<th>S/\sqrt{B}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tight-Tight</td>
<td></td>
<td>0.266</td>
</tr>
<tr>
<td>Tight-Loose</td>
<td></td>
<td>0.200</td>
</tr>
<tr>
<td>Single Tight</td>
<td></td>
<td>0.143</td>
</tr>
<tr>
<td>Loose-Loose</td>
<td></td>
<td>0.053</td>
</tr>
<tr>
<td>Single Loose</td>
<td></td>
<td>0.044</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td></td>
<td><strong>0.369</strong></td>
</tr>
</tbody>
</table>

Significant effort to optimize tagging categories and thresholds for loose/tight HOBIT selections

11% gain in S/\sqrt{B} \implies direct increase in overall search sensitivity

M. Stancari FNAL W&C 03/12
Validation of MVA Techniques

D0 and CDF single top quark
MVA-based discovery!

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Validation of MVA Techniques

Dibosons V+Z, (Z->bb) topologically similar to Higgs signal

Same final states and analysis strategy with different signal definitions.

Combine primary low-mass higgs search channels with MVAs retuned for diboson search
Validation of MVA Techniques

MVA outputs used to extract cross section

\( \sigma(WZ+ZZ) = 4.47 \pm 0.64 \text{ (stat)} \pm 0.73 \text{ (syst)} \text{ pb} \)

(SM Prediction = 4.4 \pm 0.3 \text{ pb})
MVA Improvements

Consider QCD bkgds in MET + bb

Suppressed with selection criteria:
- Large MET
- MET should not align with jet
- Jets should not be back-to-back

Remaining QCD background suppressed with BDT, based on:
- MET
- MET significance
- Track Missing pT
- Angular Variables
- etc
MVA Improvements

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Suppressed with selection criteria:
- Large MET
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Remaining QCD background suppressed with BDT, based on:
- MET
- MET significance
- Track Missing pT
- Angular Variables
- etc

MVA tuned for specific background
MVA Improvements

One final discriminant to separate signal and the remaining background after multijet veto

Medium tag sample

Tight tag sample
MVA Improvements

Reorganize events based on majority background regions
Discard nothing, but seek regions with enhanced S/B
MVA Improvements

ZH \rightarrow 2 \text{ Leptons} + b\text{-jets}

CDF Run II Preliminary 9.45/fb

All Sub-Channels

- data
- Z+lf
- Z+bb
- Z+cc
- tt
- ZZ
- WZ
- WW
- fake Z
- ZH (125) \times 50

tt-like \longleftrightarrow \text{ other}

tt expert-NN output
MVA Improvements

ZH → 2 Leptons + b-jets

CDF Run II Preliminary 9.45/ fb

All Sub-Channels

- data
- Z+If
- Z+bb
- Z+cc
- tt
- ZZ
- WZ
- WW
- fake Z
- ZH (125) × 50

Z+qq - like

other

Z+If and Z+c̅c expert-NN output
MVA Improvements

ZH → 2 Leptons + b-jets

CDF Run II Preliminary 9.45/fb

All Sub-Channels
showing: ee μμ TwoJet ThreeJet TT TL Tx LL

WZ, ZZ - like  →  ZH - like
MVA Improvements

Reorganize events based on majority background regions
Discard nothing, but seek regions with enhanced S/B
MVA Improvements

Reorganize events based on majority background regions
Discard nothing, but seek regions with enhanced S/B

Similar approaches on D0 through creation of “sub channels” based on event information
Other Improvements

NN-based jet energy correction
Use most probable jet energy based on bottom quark hypothesis

ex. improvement in mean/width of dijet mass for $H \rightarrow b \bar{b}$ ($MH=130$ GeV)

Various improvements by experiments include:
- Increase acceptance/efficiency for leptons
- New multivariate electron identification (D0)
- More optimized $b$-tag categories
  (future $c$-jet discrimination D0)
Latest limits calculated via CLs technique

Tevatron Limits on SM Higgs

Begin with combined likelihood calculations for (S+B and B-only) models

\[ L = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bins}_i}} \frac{\mu_{ij}^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}} \]

Expected events

Observed events

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Latest limits calculated via CLs technique

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$$L = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bins}_i}} \frac{\mu_{ij}^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}} \times \prod_{k=1}^{N_{np}} e^{-\theta_k^2/2}$$

Nuisance parameters

Observed events

Syst. uncertainties included as nuisance parameters affecting $\mu$'s

Determine best-fit nuisance-parameters by maximizing likelihood
Latest limits calculated via CLs technique

Tevatron Limits on SM Higgs

Begin with combined likelihood calculations for (S+B and B-only) models

Expected events

\[
L = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bins}_i}} \frac{\mu_{ij}^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}} \times \prod_{k=1}^{N_{n_p}} e^{-\theta_k^2/2}
\]

Nuisance parameters

Observed events

Syst. uncertainties included as nuisance parameters affecting \( \mu \)'s

Determine best-fit nuisance-parameters by maximizing likelihood

Test statistic based on log-likelihood ratio of hypotheses

Good agreement with Bayesian method

\[
LLR = -2 \ln \frac{p(\text{data}|S+B)}{p(\text{data}|B)}
\]

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PLHC June 2012
Limits on H→bb

<table>
<thead>
<tr>
<th>Low Mass States</th>
<th>Sensitivity $M_H = 125$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>D0</td>
</tr>
<tr>
<td>WH→llubb</td>
<td>2.8</td>
</tr>
<tr>
<td>VH→MET+bb</td>
<td>3.6</td>
</tr>
<tr>
<td>ZH→llbb</td>
<td>3.6</td>
</tr>
</tbody>
</table>

CDF Run II Preliminary $H→bb$, $L=9.5$ fb$^{-1}$

DØ Preliminary, $L_{int} \leq 9.7$ fb$^{-1}$
SM $H→b\bar{b}$ Combination

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PLHC June 2012
Limits on All Channels

<table>
<thead>
<tr>
<th>MH</th>
<th>CDF</th>
<th>D0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
<td>Expected</td>
</tr>
<tr>
<td>120</td>
<td>1.28</td>
<td>1.75</td>
</tr>
<tr>
<td>125</td>
<td>1.39</td>
<td>1.85</td>
</tr>
<tr>
<td>130</td>
<td>1.46</td>
<td>1.82</td>
</tr>
</tbody>
</table>
Tevatron Combined Limits

![Graph showing Tevatron Run II Preliminary results with L ≤ 10.0 fb⁻¹, comparing observed and expected limits for different experiments and models.](chart)

- **Tevatron Run II Preliminary, L ≤ 10.0 fb⁻¹**
- **Expected vs. Observed**
- **±1 s.d. Expected**
- **±2 s.d. Expected**
- **Tevatron + ATLAS+CMS Exclusion**
- **ATLAS+CMS Exclusion**

**Axes:**
- **m_H (GeV/c²)**
- **95% CL Limit/SM**

**Key Points:**
- February 2012
- SM=1

---

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Tevatron Combined Limits

Expected Sensitivity
Better than 1.13xSM
MH < 185 GeV
Tevatron Combined Limits

Observed Exclusion:
100 < m_H < 106 GeV
147 < m_H < 179 GeV
Tevatron Combined Limits

Quantifying this excess?
LLR of Tevatron Combination

Compare to signal expectation

\[
LLR = -2 \ln \frac{p(\text{data}|S + B)}{p(\text{data}|B)}
\]

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

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p-value of Tevatron Combination

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

Background p-value

February 2012

Higgs Boson Mass (GeV/c^2)
Best Fit to Signal Model

\[ \sigma_H \times BR(H \rightarrow X)/SM \]

Tevatron RunII Preliminary

\[ L_{\text{int}} \leq 10.0 \text{ fb}^{-1} \]

February 2012
H-$\rightarrow$bb Limits for Tevatron Combination

![Graph showing Higgs boson mass limits for Tevatron Run II Preliminary. The graph displays the 95% CL limit on the Higgs boson mass as a function of the mass, with observed and expected limits indicated by different shadings. The limits are compared to the Standard Model expectations.](Image)
H→bb LLR for Tevatron Combination

Tevatron RunII Preliminary

SM H→b\bar{b}, L_{int} \leq 10.0 fb^{-1}

February 2012
H→bb p-value for Tevatron Combination

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

February 2012

Higgs Boson Mass (GeV/c²)
H→bb Fit for Tevatron Combination

Tevatron Run II Preliminary

SM H→bb, L_{int} ≤ 10.0 fb^{-1}

- Best Fit
- ±1 s.d.

February 2012
Significance of Excess

Significance of a local excess is diluted by look-elsewhere effect.

From studies of mass resolution, assume 4 independent search regions in $100 < m_H < 200$ GeV.

Global $p$-value $\approx 4 \times$ minimum local $p$-value

<table>
<thead>
<tr>
<th></th>
<th>Local Significance</th>
<th>Global Significance</th>
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<tbody>
<tr>
<td>CDF</td>
<td>2.6 $\sigma$</td>
<td>2.1 $\sigma$</td>
</tr>
<tr>
<td>D0</td>
<td>2.2 $\sigma$</td>
<td>1.5 $\sigma$</td>
</tr>
<tr>
<td>Tevatron</td>
<td>2.7 $\sigma$</td>
<td>2.2 $\sigma$</td>
</tr>
</tbody>
</table>

Similar-sized excesses in complementary searches at the LHC and Tevatron.
Conclusions

Analysis improvements implemented in CDF and D0 to improve Higgs sensitivity to better than 1.13×SM for m_H < 185 GeV

Broad excess in observed data relative to background-only hypothesis in 105 < m_H < 145 GeV

Global significance of excesses of all channels is 2.2 σ

Latest Tevatron combination is underway:
   Significant updates from all D0 analyses
   Inclusion of improved b-tagging in CDF MET + b-jets
Backup Slides
Tevatron Combined Limits

Expected Exclusion
100 < m_\(H\) < 119 GeV
141 < m_\(H\) < 184 GeV
Limits on H→WW

CDF Run II Preliminary  H→WW  L = 9.7 fb⁻¹

95% CL Limit/S&M

SM=1

February 28, 2012

DØ Preliminary, L_{int} ≤ 9.7 fb⁻¹

SM H→WW Combination

95% CL Limit on σ/σ_{SM}

Feb 24 2012

Higgs Boson Mass (GeV/c²)
Significance of Excess

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<tr>
<td>Tevatron</td>
<td>2.7 $\sigma$</td>
<td>2.2 $\sigma$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>3.5 $\sigma$</td>
<td>2.2 $\sigma$</td>
</tr>
<tr>
<td>CMS</td>
<td>2.8 $\sigma$</td>
<td>2.1 $\sigma$</td>
</tr>
</tbody>
</table>
# List of Channels (CDF)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity (fb⁻¹)</th>
<th>m_H range (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH → ℓνbb 2-jet channels</td>
<td>4×(TT,TL,Tx,LL,Lx)</td>
<td>9.45</td>
</tr>
<tr>
<td>WH → ℓνbb 3-jet channels</td>
<td>3×(TT,TL)</td>
<td>9.45</td>
</tr>
<tr>
<td>ZH → ℓνbb (SS,SJ,1S)</td>
<td>9.45</td>
<td>100-150</td>
</tr>
<tr>
<td>ZH → ℓ⁺ℓ⁻bb 2-jet channels</td>
<td>2×(TT,TL,Tx,LL)</td>
<td>9.45</td>
</tr>
<tr>
<td>ZH → ℓ⁺ℓ⁻bb 3-jet channels</td>
<td>2×(TT,TL,Tx,LL)</td>
<td>9.45</td>
</tr>
<tr>
<td>H → WW⁻⁺⁻⁺⁻ (same-sign leptons)+(tri-leptons)</td>
<td>9.7</td>
<td>110-200</td>
</tr>
<tr>
<td>H → WW⁻⁺⁻⁺⁻ (e⁻τHad)+(μ⁻τHad)</td>
<td>9.7</td>
<td>130-200</td>
</tr>
<tr>
<td>WH → WW⁺⁺⁻⁻ tri-leptons with 1 τ_Had</td>
<td>9.7</td>
<td>130-200</td>
</tr>
<tr>
<td>WH → WW⁺⁺⁻⁻ (trileptons with 1 jet)+(trileptons with 2 or more jets)</td>
<td>9.7</td>
<td>110-200</td>
</tr>
<tr>
<td>H → ZZ four leptons</td>
<td>9.7</td>
<td>120-200</td>
</tr>
<tr>
<td>H + X → τ⁺⁻⁻⁻ (1 jet)+(2 jets)</td>
<td>8.3</td>
<td>100-150</td>
</tr>
<tr>
<td>WH → ℓντ⁺⁻⁻⁻ /ZH → ℓ⁺⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻⁻˓</td>
<td>9.45</td>
<td>100-150</td>
</tr>
</tbody>
</table>
# List of Channels (D0)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Luminosity $\text{(fb}^{-1}\text{)}$</th>
<th>$m_H$ range $\text{(GeV}/c^2\text{)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WH \rightarrow \ell \nu bb$ (TST,LDT,TDT) $\times (2,3$ jet)</td>
<td>9.7</td>
<td>100-150</td>
</tr>
<tr>
<td>$ZH \rightarrow \nu \bar{\nu} bb$ (MS,TS)</td>
<td>9.5</td>
<td>100-150</td>
</tr>
<tr>
<td>$ZH \rightarrow \ell^+ \ell^- b \bar{b}$ (TST,TLDT) $\times (ee,\mu \mu,ee_{ICR},\mu \mu_{\tau r k}$</td>
<td>9.7</td>
<td>100-150</td>
</tr>
<tr>
<td>$H+X \rightarrow \ell^\pm \tau^\mp_{\text{had}}jj$</td>
<td>4.3-6.2</td>
<td>105-200</td>
</tr>
<tr>
<td>$VH \rightarrow e^\pm \mu^\pm + X$</td>
<td>9.7</td>
<td>115-200</td>
</tr>
<tr>
<td>$H \rightarrow W^+ W^- \rightarrow \ell^\pm \nu \ell^\mp \nu$ $(0,1,2+ \text{ jet})$</td>
<td>8.6-9.7</td>
<td>115-200</td>
</tr>
<tr>
<td>$H \rightarrow W^+ W^- \rightarrow \mu \nu \tau_{\text{had}} \nu$</td>
<td>7.3</td>
<td>115-200</td>
</tr>
<tr>
<td>$H \rightarrow W^+ W^- \rightarrow \ell \nu jj$</td>
<td>5.4</td>
<td>130-200</td>
</tr>
<tr>
<td>$VH \rightarrow \ell \ell \ell + X$</td>
<td>9.7</td>
<td>100-200</td>
</tr>
<tr>
<td>$VH \rightarrow \tau \tau \mu + X$</td>
<td>7.0</td>
<td>115-200</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>9.7</td>
<td>100-150</td>
</tr>
</tbody>
</table>