Higgs boson searches at Tevatron

- On the way of the Higgs:
  - Di-bosons
  - Standard Model expectations
- Higgs searches introduction
- Low mass Higgs analysis
- Low mass Higgs combination
- High mass Higgs analysis
- Final Higgs searches combination
- Next step
On the way to the Higgs: Di-bosons

Diboson final states:
➢ Test Standard Model production predictions
➢ Look for anomalous coupling
➢ Cross sections similar to Higgs

CDF & D0 published results on:

New D0 measurement using 1fb$^{-1}$
On the way to the Higgs: WW

Final states: $ee$, $\mu\mu$, $e\mu$

Example of variables used as input for the Matrix Element

$P(\vec{x}_{\text{obs}}) = \frac{1}{\langle \sigma \rangle} \int \frac{d\sigma(\vec{y})}{d\vec{y}} \epsilon(\vec{y}) G(\vec{x}_{\text{obs}}, \vec{y}) d\vec{y}$

True leptons momenta

LO cross section

Efficiency and acceptance

Physics observables

Likelihood ratio:

$LR_{WW} = \frac{P_{WW}}{P_{WW} + \sum_i k_i P_i}$
On the way to the Higgs: WW

Cross section

\[ \sigma(pp \rightarrow WW) = 12.1 \pm 0.9 \text{(stat)} \pm 1.6 \text{(syst)} \text{ [pb]} \]
On the way to the Higgs: ZZ

Results using final states with:

4 leptons

2 leptons and 2 $\nu$

Combining the two channels D0 $(2.7 \text{ fb}^{-1})$ signal has $5.7\sigma$ significance

The cross section $\sigma(ZZ) = 1.60 \pm 0.63^{+0.16}_{-0.17} (\text{stat.}) (\text{syst.})$

Combining the two channels CDF signal has $4.4\sigma$ significance

The cross section $1.4^{+0.7}_{-0.6} (\text{stat.} + \text{syst.}) \text{ pb}$
Top Mass

Use up to 3.6 fb\(^{-1}\) of data

CDF and D0 combined:

\[ M_t = 173.1 \pm 0.6 \text{(stat)} \pm 1.1 \text{(syst)} \text{GeV/c}^2 \]

Total uncertainty 1.3 GeV/c\(^2\) --> relative precision of 0.75%
W Boson Mass

Latest results D0: 
\[ M_W = 80.401 \pm 0.044 \text{ GeV} \]

CDF has in progress the analysis on 2.4fb\(^{-1}\) the expected statistical error is \(~15\text{ MeV}\)
Cornering the Higgs

http://gfitter.desy.de/
Direct Higgs searches @ Tevatron

Low Mass: $M_H < 135 \text{ GeV/c}^2$

High Mass: $M_H > 135 \text{ GeV/c}^2$
Analysis Tools: Lepton Identification

➢ Identify the decay of W/Z
  ✔ electrons: tracks matched to ECAL
  ✔ muons: tracks matched to muon chambers
  ✔ taus: tracks matched to calorimeter cluster

➢ Expand lepton coverage:
  ✔ interplay between sub-detectors to cover holes
  ✔ include forward detectors
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➢ Good Missing $E_T$ (MET) trigger:
  ✔ select events with neutrinos and charged lepton that fail ID
  ✔ remove events with fake MET
Analysis Tools: b-jet identification

- **B-tagging**:
  - exploit long lifetime of b-hadrons
  - Suppress light flavor background
  - Improves S/B

- Various algorithms used by CDF/D0
  - Identify displaced vertex
  - Exploit multiple feature of b-jets
  - Probability that tracks come from primary vertex
  - b-tagging efficiency: 40-70%

- D-jet invariant mass
Analysis Tools: Multivariate techniques

- Maximize discriminating power using global kinematics of signal and background
  - Machine learning techniques: Neural Network and Boost Decision Tree (BDT)
  - For each event calculate the probability to come from signal from LO Matrix Element

- Multivariate techniques help to improve sensitivity

- Used already in many many analysis
Reminder: Limit Plots

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

$ZH \rightarrow l^+l^- b\bar{b}$

$95\%$ CL Upper Limit/SM

$M_H$ (GeV/c$^2$)

Expected limit

Observed limit

2σ uncertainty on expected limit

1σ uncertainty on expected limit

Observed limit

Expected limit

σ uncertainty on expected limit
Low Mass Higgs searches

Low Mass: $M_H < 135 \text{ GeV}/c^2$

Dominant production mechanism: $gg \rightarrow H$

Dominant decay mode: $H \rightarrow bb\bar{b}$
Low Mass Higgs searches

Decay channels

➢ Look for as many final states as possible with $H \rightarrow b \bar{b}$, highest BR
➢ $gg \rightarrow H \rightarrow b \bar{b}$ dominant production mode not available right now due to background.

These data are collected with b-tag trigger designed and implemented by “us”

<table>
<thead>
<tr>
<th>Trigger algorithms</th>
<th>$\epsilon(H \rightarrow bb)$</th>
<th>$\epsilon(\phi \rightarrow bb)$</th>
<th>$\epsilon(Z \rightarrow bb)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex b-tag</td>
<td>13%</td>
<td>11%</td>
<td>4%</td>
</tr>
<tr>
<td>Muon b-tag</td>
<td>5%</td>
<td>6%</td>
<td>2%</td>
</tr>
</tbody>
</table>

Table 1: Trigger efficiencies for $H$, $\phi$ and $Z$ decays

Useful for $Z \rightarrow bb$, b-jet energy study
Low Mass Higgs searches cont'd

- Look for VH and ZH associated production:
  - Higgs decays in two high pT b-jets
  - Leptonic decays of W/Z reduce QCD background and allow easy trigger strategy

- Reconstruct also $H\rightarrow\gamma\gamma$ and $H\rightarrow\tau\tau$ with gluon-gluon fusion, associated production and Vector Boson Fusion
Low Mass Higgs: Strategy

➢ Efficient trigger to keep most of potential Higgs candidates
  ✗ high pt charged leptons: $e \mu$ to select W/Z
  ✗ missing $E_T$+jets to select $HZ$, $Z\rightarrow \nu\nu$ or $HW$ $W\rightarrow l\nu$ ($l$ not identified)
  ✗ lepton+track for $\tau\tau$ modes

➢ Increase signal yields
  ✗ increase lepton acceptance improving $e/\mu$ ID
  ✗ more efficient b-tag algorithms
  ✗ better understanding of calorimeter response

➢ Look for a resonance in dijets mass
  ✗ large backgrounds with large uncertainties
  ✗ use multivariate techniques to separate signal from background
Low Mass Higgs: $ZH \rightarrow \ell^{+}\ell^{-}b\bar{b}$, $\ell = e, \mu$

Signature: 2 high Pt leptons and 2+ b-jets
Trigger Path: single lepton
CDF: 2.7 fb$^{-1}$ D0: 3.1 – 4.2 fb$^{-1}$
Major backgrounds: Z + jets/heavy flavors, top, di-bosons
Small $\sigma \times$BR ~ 1 event/fb$^{-1}$ Important to increase acceptance
Low Mass Higgs: \( ZH \rightarrow \ell^+ \ell^- b \bar{b}, \ell = e, \mu \)

Use multivariate techniques to improve S/B

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Lumi Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>115 fb(^{-1})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDF ME</td>
<td>2.7</td>
<td>12.3</td>
</tr>
<tr>
<td>CDF NN</td>
<td>2.7</td>
<td>9.9</td>
</tr>
<tr>
<td>D0 BDT</td>
<td>3.1</td>
<td>8</td>
</tr>
</tbody>
</table>

\( M_H = 120 \text{ GeV}/c^2 \)
Low Mass Higgs: \( WH \rightarrow \ell v b\bar{b}, \ell = e, \mu \)
Signature: 1 high Pt lepton large MET and 2+ b-jets
Trigger path: single lepton
CDF and D0 : 2.7 fb\(^{-1}\)
Major backgrounds: W+bb-jets, top, multijets
“Large” \( \sigma \times \text{BR} \sim 3-4 \) event/fb\(^{-1}\)
**Low Mass Higgs:** \( WH \rightarrow \ell \nu b\bar{b}, \ell = e, \mu \)

Multivariate techniques to improve S/B:

**D0:** NN

**CDF:** NEAT = BDT + NN + ME

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Lumi</th>
<th>Expected limit</th>
<th>Observed limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_H = 115 ) fb(^{-1} )</td>
<td>2.7</td>
<td>4.8</td>
<td>5.6</td>
</tr>
<tr>
<td>CDF NEAT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D0 NN+ME</td>
<td></td>
<td>6.4</td>
<td>6.7</td>
</tr>
</tbody>
</table>
Low Mass Higgs: $VH \rightarrow \vec{E}_T b\bar{b}$

Signal acceptance ZH-$\rightarrow$vvbb and WH-$\rightarrow$vbb (l missed)

Signature: large MET and 2+ b-jets

Trigger Path: MET

CDF and D0: 2.1 fb$^{-1}$

Major backgrounds: QCD with fake MET, W/Z+bb-jets, top, diboson

Background modeled using data
Low Mass Higgs: $VH \rightarrow \not{E}_T b\bar{b}$

Multivariate techniques to improve S/B:
DO: BDT on double tagged sample
CDF: NN with separate training for 2 and 3 jets

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Lumi</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_H = 115$</td>
<td>2.1</td>
<td>5.6</td>
<td>6.9</td>
</tr>
<tr>
<td>CDF NN</td>
<td>2.1</td>
<td>8.4</td>
<td>7.5</td>
</tr>
<tr>
<td>DO BDT</td>
<td>2.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Low Mass Higgs Combination

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

$M_H = 115$ Expected limit 3.22
Observed limit 3.64
Low Mass Higgs Combination

$M_H = 115$ Expected limit 3.80
Observed limit 3.60
Low Mass Higgs Tevatron Combination

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

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

$M_H = 115$

Expected limit 2.4
Observed limit 2.5
High Mass Higgs: \( H \rightarrow WW \)

Signal:

0 jets at LO (gg\( \rightarrow \)H)

2 jets at LO (ZH/WH/VBF)

Separate in 0, 1, 2+ jets bin because of different backgrounds
High Mass Higgs: \( H \rightarrow WW \)

**Signal:**
- 0 jets at LO (gg→H)

**Background:**
- LO: WW, Drell Yan, W+ν

**Signal:**
- 2 jets at LO (ZH/WH/VBF)

**Background:**
- LO: WZ, ZZ, \( tt \)
High Mass Higgs:  \( H \to WW \)

0 jets:
Good use of LO ME
majority of signal gg fusion
background from WW

1 jet:
ME not so powerful
extra signal: VH and VBF ~20%

2 jets:
tt main background
extra signal: VH and VBF ~60%
High Mass Higgs: $H \rightarrow WW$

Apply selection cut:
- 2 opposite sign isolated leptons
- di-lepton opening angle
- significant MET

Then use combinations of ME and NN depending on jet bin
High Mass Higgs: add other final states

- Two lepton Pt>20 GeV
- No forward electrons
- Njets≥1
- No MET cut

Add 5% sensitivity

<table>
<thead>
<tr>
<th>Process</th>
<th>$\mathcal{L}$ (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt$</td>
<td>$0.11 \pm 0.03$</td>
</tr>
<tr>
<td>DY</td>
<td>$11.99 \pm 3.65$</td>
</tr>
<tr>
<td>$WW$</td>
<td>$0.020 \pm 0.005$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$6.82 \pm 0.93$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$1.44 \pm 0.20$</td>
</tr>
<tr>
<td>$W+$jets</td>
<td>$22.45 \pm 6.73$</td>
</tr>
<tr>
<td>$W\gamma$</td>
<td>$3.23 \pm 1.00$</td>
</tr>
<tr>
<td>Total Background</td>
<td>$46.07 \pm 8.02$</td>
</tr>
<tr>
<td>$WH$</td>
<td>$1.19 \pm 0.16$</td>
</tr>
<tr>
<td>$ZH$</td>
<td>$0.19 \pm 0.02$</td>
</tr>
<tr>
<td>Total Signal</td>
<td>$1.38 \pm 0.18$</td>
</tr>
<tr>
<td>Data</td>
<td>41</td>
</tr>
</tbody>
</table>
High Mass Higgs: Systematics

Two classes

➢ Rate Systematics:
   ✔ affect only templates normalization, do not affect the shapes
   ✔ dominant theoretical cross section uncertainties, 10-30%

➢ Shape systematics:
   ✔ modify the shape of NN output
   ✔ Found negligible up to now
     (PDF modeling, Energy scale, Pt scale)
High Mass Higgs Combination

Latest $gg\rightarrow H$ cross section (Florian and Grazzini)

- Latest PDF MSTW2008
- NNLL QCD
- NLO b-quark treatment
- VH from hep-ph/0406152
- VBF from TEV4LHC

$M_H = 160$ Expected Observed

<table>
<thead>
<tr>
<th>0 jets</th>
<th>2.39</th>
<th>2.35</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 jet</td>
<td>2.89</td>
<td>2</td>
</tr>
<tr>
<td>2+ jets</td>
<td>3.71</td>
<td>6.34</td>
</tr>
<tr>
<td>SS +jet</td>
<td>7.22</td>
<td>6.6</td>
</tr>
<tr>
<td>Combined</td>
<td>1.52</td>
<td>1.37</td>
</tr>
</tbody>
</table>
**High Mass Higgs:** $H + X \rightarrow l\ell + \text{missing } E_T$

Analysis separated by lepton type: $ee$, $\mu\mu$, $e\mu$

Apply minimal requirements then use NN

Sample composition input to NN

<table>
<thead>
<tr>
<th>Channel</th>
<th>ee</th>
<th>$e\mu$</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity (fb$^{-1}$)</td>
<td>4.2</td>
<td>4.2</td>
<td>3.0</td>
</tr>
<tr>
<td>$Z$</td>
<td>108</td>
<td>13</td>
<td>3987</td>
</tr>
<tr>
<td>Diboson</td>
<td>84</td>
<td>162</td>
<td>127</td>
</tr>
<tr>
<td>$tt$</td>
<td>40</td>
<td>82</td>
<td>13</td>
</tr>
<tr>
<td>$W+$jets</td>
<td>98</td>
<td>79</td>
<td>134</td>
</tr>
<tr>
<td>Multijets</td>
<td>2</td>
<td>1</td>
<td>64</td>
</tr>
<tr>
<td>Total Background</td>
<td>332</td>
<td>337</td>
<td>4325</td>
</tr>
<tr>
<td>Data</td>
<td>336</td>
<td>329</td>
<td>4084</td>
</tr>
<tr>
<td>Signal ($M_H = 165$ GeV)</td>
<td>6.1</td>
<td>12.2</td>
<td>4.9</td>
</tr>
</tbody>
</table>

NN output
High Mass Higgs Combination

Use the same systematic of CDF, same inputs

$M_H = 165$
expected limit 1.7
observed limit 1.3

It does not include SS
Tevatron Combination

Not just a $\sqrt{2}$ factor, many systematics are correlated between CDF and D0

We exclude SM Higgs in a mass range 160-170 GeV at 95% CL
Future Prospects: Low Mass

Includes “standard analysis” improvements:
- extended b-tag “a la top”
- better background understanding
- more sophisticated analysis techniques

It does not include new triggers:
- more efficient MET
- b-tag trigger

End of 2010/2011

Efficiency respect to double tag events
Future Prospects: High Mass

Plan to include:
- new lepton triggers (by the summer)
- lower cut on MET (by summer)
- tri-leptons (summer)
- lepton isolation (next year)
- low di-lepton mass