Searches for Higgs Boson at the Tevatron

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Higgs Today

• At least one SM-like Higgs is required in most models
  – Use SM Higgs for benchmarking, but keep in mind that it can be something more complex

• Direct exclusions:
  – LEP: m>114 GeV

• Indirect:
  – LEP, Tevatron (W/top mass)
  – 95% C.L. m<158 GeV

• Non-SM scenarios (e.g. NMSSM) can weaken both direct and indirect limits
Higgs Production at the Tevatron

- Dominated by gluon fusion
  - But large decay modes often come with large backgrounds

- Associated Production
  - While smaller cross section, offers cleaner final states

- Vector Boson Fusion (VBF)
  - Even smaller cross-section, but can help increase the overall sensitivity

- Have to be inventive and use all accessible modes and many decay channels
  - Improving analysis techniques
Higgs Search Strategies

• Sensitivity strongly depends on backgrounds for a specific decay channel:
  • “High mass” $m > \sim 135$ GeV:
    – WW (and ZZ) decay modes
      • Clean final states with leptons, any production mode will do
  • “Low mass” $m < \sim 135$ GeV:
    – Associated production:
      • Rely on leptons/neutrinos to reduce background, go after all decay modes (but bb dominates)
    – Gluon fusion:
      • $H \rightarrow bb$ dominated by backgrounds
      • $H \rightarrow \tau\tau$: ok but small BR
Higgs Searches at the Tevatron

HIGH MASS HIGGS
High Mass Searches

• WW is the best channel
  – Large BR, can use all production modes
• Both experiments rely on advanced techniques and categorizations
  – Neural Net (NN), Matrix Element (ME), Decision Trees (DT)
• Backgrounds:
  – DY, diboson, W+jets
• Selections:
  – 2 OS leptons, MET
  – Leptons+jets
  – LS leptons (WH->WWW)

• Helicity conservation:
  – Leptons tend to go in the same directions
Signal Extraction

• Categorize according to $N_{\text{jet}} = 0, 1, 2$ in $ll + N_{\text{jets}}$
  – Adds VBF and associated production with $H \rightarrow WW$
• CDF uses NNs, DO - BDTs
  – Trained on each category separately
  – Inputs: event topology (lepton kinematics, lepton and MET, jets and MET) and quality of leptons
High Mass: Results

• Combine together multiple analysis channels
  – CDF example shows importance of different contributions

\[ M_H = 165 \]

<table>
<thead>
<tr>
<th>CDF Run II</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 jets</td>
<td>1.67</td>
<td>2.39</td>
</tr>
<tr>
<td>1 jet</td>
<td>2.35</td>
<td>2.46</td>
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<tr>
<td>2+ jets</td>
<td>3.16</td>
<td>6.14</td>
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<tr>
<td>SS 1+jet</td>
<td>4.86</td>
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<tr>
<td>Tri-lep. NoZ</td>
<td>7.37</td>
<td>7.85</td>
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<tr>
<td>Tri-lep. Z1J</td>
<td>31.8</td>
<td>36.4</td>
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<tr>
<td>Tri-lep. Z2+J</td>
<td>9.16</td>
<td>10.4</td>
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<tr>
<td>Hadr. Tau</td>
<td>14.5</td>
<td>23.5</td>
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<tr>
<td>Low Mll</td>
<td>11.2</td>
<td>7.21</td>
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<tr>
<td>Combined</td>
<td>1.00</td>
<td>1.08</td>
</tr>
</tbody>
</table>

• Combine CDF and D0
• Excluded mass range:
  – 158-175 GeV/c²
Higgs Searches at the Tevatron

LOW MASS HIGGS
Associated Production Channels

- While smaller cross-section, final states are much cleaner
- Main ingredients:
  - Leptons or MET allow large reduction in backgrounds to go after dominant bb decay channel
  - b-tagging dramatically reduces W/Z+light jet and QCD backgrounds
- Analyses look for a bump in the dijet spectrum
  - Good understanding of bb mass resolution is critical
Backgrounds and Resolution

- After 1 or 2 b-tags
  Signal region with enhanced signal / background
Multivariate Techniques

- Both experiments rely on advanced techniques
  - NN, ME, DT
    - Validated in other analyses, requires excellent understanding of the detectors
  - Extensive categorization to improve sensitivity
    - E.g. 4 b-taggers (displaced vertex, track impact parameter, NN)
    - Multiple lepton categories including lose ones to increase acceptance

- Bayesian NN output in WH->lvbb analysis
Low Mass Limits

- Data consistent with expectation
- Sensitivity ranking list of channels
  - Use CDF as an example

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected $\sigma$(excl)/$\sigma$(SM) for $m=115$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH→$l\nu bb$</td>
<td>&lt;3.5</td>
</tr>
<tr>
<td>VH in MET+bb</td>
<td>&lt;4.0</td>
</tr>
<tr>
<td>ZH→$ll bb$</td>
<td>&lt;5.5</td>
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<tr>
<td>VH in qqbb</td>
<td>&lt;18</td>
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<tr>
<td>$\gamma\gamma$</td>
<td>&lt;21</td>
</tr>
<tr>
<td>2$\tau$+2j</td>
<td>&lt;23</td>
</tr>
<tr>
<td>Combined</td>
<td>&lt;1.9</td>
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</tbody>
</table>
“New” Low Mass Channel: $H \rightarrow \gamma \gamma$

- “Discovery” mode at the LHC
  - Small BR~0.2%, but a narrow bump
    - Sensitivity is a strong function of EM calorimeter resolution

- Useful experience in preparing for $H \rightarrow \gamma \gamma$ at the LHC
CDF & D0 Combinations

- CDF limits
- D0 limits

@ $m_H = 100$ GeV, both set observed limits below expected
Closing in on low mass LEP exclusion
Low mass sensitivity approaching LEP exclusion $m_H > 109$ GeV:
- Expected $1.45 \times \text{SM} @ 115$ GeV
- Expected $1.24 \times \text{SM} @ 105$ GeV

High mass 95% CL exclusion:
- $158 < m_H < 175$ GeV
  - Expected $(156 < m_H < 175$ GeV)
What Would a Signal Look Like?

- Perform the following test:
  - Inject signal with $m_H = 115$ GeV into pseudoexperiments
    - $ZH \rightarrow llbb, WH \rightarrow lvbb, ZH \rightarrow vvbb$
  - Result: slight excess
    - Similar to observed limits
MSSM Higgs

- Higgs coupling enhancement at large $\tan\beta$:
  - Large increase in cross-sections compared to SM
    - E.g. $gg \rightarrow h/A$, $gb \rightarrow bA$
  - Dominant $gg \rightarrow H \rightarrow bb$ is still difficult, but new final states:
    - $H \rightarrow \tau\tau$, $Hb \rightarrow bbb$, $b\tau\tau$, $Hbb \rightarrow bbbb$, $bb\tau\tau$

- Combined 2 ifb result for $h \rightarrow \tau\tau$
MSSM Higgs

- MSSM Higgs 3b search \((\Phi+b \rightarrow bb+b)\)
  - Complements MSSM \(H \rightarrow \tau\tau\) search
  - Relies on CDF’s trigger-level b-tagging used in b physics
  - New version of analysis 2x more acceptance
    - \(m_H = 140\) GeV most significant excess

\[\text{P-value} = 0.9\% \text{ (5.7\% with trials factor)}\]
New MSSM Higgs search

- D0’s $\Phi \to \tau\tau+b$
  - Does not suffer from radiative corrections increasing Higgs width in $\Phi \to bb+b$
  - Exclusive from $\Phi \to \tau\tau$
  - Provides similar sensitivity
Luminosity Projections

~16 fb\(^{-1}\) :*
> 3 \(\sigma\) expected sensitivity from 100 – 185 GeV
4 \(\sigma\) @ 115 GeV

End of 2011: > 2.4 \(\sigma\) expected sensitivity across mass range
3 \(\sigma\) at 115 GeV

* 16 fb\(^{-1}\) : based on “Run III” proposal to run 3 more years
Summary

• Both CDF and D0 have an extensive program of searches for Higgs
  – Significant improvement in terms of better use of the data:
    • More complex techniques possible given excellent understanding of the detectors and extensive experience
    • Improved acceptances and categorization lead to better sensitivities
  – Tevatron SM Higgs sensitivity approaches exclusion of the entire range $m<180$ at 95% CL
• Evidence for Higgs may be not too far away
What goes into the combination?
# Improvements for 115 GeV Higgs for CDF

<table>
<thead>
<tr>
<th>Type</th>
<th>Projected improvements</th>
<th>WHlvbb, %</th>
<th>ZHllbb, %</th>
<th>VHMETbb, %</th>
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<tbody>
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<td>TRIGGERS</td>
<td>Single stub muons</td>
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<td>3</td>
<td>NO</td>
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<td></td>
<td>Complete OR</td>
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<td>8</td>
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<td>JET EN RESOL.</td>
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<td>DONE</td>
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<td>B-specific NN</td>
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<td>TOTAL</td>
<td>All improvements</td>
<td>90%</td>
<td>60%</td>
<td>70%</td>
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</tbody>
</table>

(Multiplicative total: 1.05*1.05*1.15...)

- 115 GeV Higgs searches dominated by WH→lvbb, ZH→llbb, VH→METbb
- ~50% gain required in each channel to reach projected sensitivity

Fermilab PAC, August 2010