Search for high mass standard model Higgs boson at D0

Boris Tuchming - CEA Saclay
On behalf of D0 collaboration

Z^0\gamma

ICHEP 2010

ICHEP10, Paris – D0 search for high mass Higgs
The Tevatron

Run I (1993-1996)
~120 pb\(^{-1}\) per experiment - top quark discovery

Run II: (2002-201xx)
~ 9 fb\(^{-1}\) delivered per experiment
Tevatron now delivers >2 fb\(^{-1}\) per year

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Run II

<table>
<thead>
<tr>
<th>Year</th>
<th>Integrated Luminosity (pb(^{-1}))</th>
</tr>
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<tbody>
<tr>
<td>2002</td>
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<td>2003</td>
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<td>2008</td>
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</tr>
<tr>
<td>2009</td>
<td>12000</td>
</tr>
<tr>
<td>2010</td>
<td>14000</td>
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- Run 2a
- Run 2b
The Tevatron and D0

Run I (1993-1996)
~120 pb$^{-1}$ per experiment - top quark discovery

Run II: (2002-201xx)
~ 9 fb$^{-1}$ delivered per experiment
Tevatron now delivers >2 fb$^{-1}$ per year

D0 most recent results are based on 6.7 fb$^{-1}$
(data recorded up to spring 2010)

Run II

Integrated Luminosity 9.0 (1/pb)

<table>
<thead>
<tr>
<th>Year</th>
<th>Luminosity (1/pb)</th>
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</thead>
<tbody>
<tr>
<td>2002</td>
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<td>2007</td>
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<td>2008</td>
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<td>2009</td>
<td>7,000</td>
</tr>
<tr>
<td>2010</td>
<td>9,000</td>
</tr>
</tbody>
</table>

Run 2a Run 2b
Production cross section (for $115 < m_H < 180$ GeV)

- In the 1200-300 fb range for gluon fusion $gg \rightarrow H$
- In the 200-30 fb range for $WH$ associated vector boson production
- In the 80-30 fb range for the vector boson fusion $qq \rightarrow Hqq$

$$\sigma(p\bar{p}\rightarrow H+X) [pb]$$

$\sqrt{s} = 2$ TeV
$M_t = 175$ GeV
CTEQ4M

$\sigma_H$ vs $M_H$ [GeV]
Decay modes depend on the Standard Model Higgs mass

At high mass:
- Look for W decay products
- Peak sensitivity just above threshold $M_H \sim 165$ GeV.

$m_H < 135$ GeV
- $H \rightarrow \tau\tau$
- $H \rightarrow bb$

$m_H > 135$ GeV
- $H \rightarrow WW^*$
Backgrounds to WW final states

- W+jets
  - Alpgen MC+ pythia showering
  - NNLO cross-sections
  - corrections to model $p_T(W), p_T(Z)$

- Z/γ

- WW
  - Di-boson WW, WZ, ZZ
    - NLO calculation for cross-sections
    - for WW: NLO correction for $p_T$ and di-lepton opening angle

- WZ

- Top
  - Top pair and single top
    - cross-section normalized at NNLO

- multijet
  - QCD multijet events
Backgrounds to WW final states

- $W+\text{jets}$
- $Z/\gamma$
- $WW$
- $WZ$
- Top
- multijet

The Higgs signal is several order of magnitude below backgrounds
Looking for $H \rightarrow WW^*$

- W decay modes determine the final states
  - $W \rightarrow$ hadrons $\sim 68\%$
  - $W \rightarrow$ lepton+neutrino $\sim 3 \times 11\%$

- At hadronic collider: need for lepton and/or missing $E_T$ signature because of overwhelming QCD background

- Di-lepton + missing $E_T$ signature
  - Small $Br \sim 6\%$ (ee, $e\mu$, $\mu\mu$)
  - Clean signal

- Lepton + jets signature
  - Larger $Br \sim 30\%$ ($e+$jets, $\mu+$jets)
  - Large $W+$jets background, hard to model

- Special case of associated production: $HW \rightarrow W W W$
  - Same sign charged leptons are a very clean signature
  - But small $\sigma \times Br$
Di-lepton + \(E_T\) channel

- **Signature:**
  - 2 isolated high \(p_T\) leptons
  - Large missing \(E_T\)
  - Higgs is scalar + V-A interaction
    - The leptons tend to be collinear
    - Small di-lepton mass
    - Small \(\Delta\phi(l,l)\)

- **Strategy**
  - Split analysis according to lepton flavor
  - Different instrumental (fake) background
  - Different lepton momentum resolution
    - typically 4% for electrons, 10% for muons
  - Different background composition
  - split e\(\mu\) analysis according to jet multiplicity (0, 1, \(\geq 2\))
    - Better discrimination against top events (also use b-tagging)
    - Better sensitivity to \(H+\)jets final states: \(qqH, WH, ZH\) (important for low mass)
  - For new e\(\mu\) analysis: more optimized lepton-id criteria \(\sim +15\%\) acceptance

\[m_H = 165 \text{ GeV}\]

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**Preliminary**

- \(e\mu\) 6.7 fb\(^{-1}\)
- \(ee+e\mu+\mu\mu\) 5.4 fb\(^{-1}\)

*PRL. 104, 061804 (2010)*
Di-lepton + $\mathcal{E}_T$ selection

- **Preselection:**
  - $p_T(\text{lepton}) > 10-20$ GeV
  - Isolation, opposite charge, $M_{l_1, l_2} > 15$ GeV

- **Selection**
  - Loose kinematics cuts to get rid of the dominant background

Cut on $\Delta \phi(l,l)$, $\mathcal{E}_T$, $\mathcal{E}_T^{\text{spec}}$, $\mathcal{E}_T^{\text{scale}}$, $M_T(\text{lep}, \mathcal{E}_T)$

$\mathcal{E}_T$ based variables to ensure $\mathcal{E}_T$ is significant and not due to mismeasured object.
Still large background after selection

- For $\mu\mu$ ($m_H=165$ GeV)
  - $S/B \sim 9/1600$
  - $S/\sqrt{B} \sim 0.22$
- For $ee$ ($m_H=165$ GeV)
  - $S/B \sim 7/423$
  - $S/\sqrt{B} \sim 0.34$

Di-lepton + $E_T$ figures

- $ee+\mu\mu$ 5.4 fb$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>$e^+e^-$ Preselection</th>
<th>$e^+e^-$ Final selection</th>
<th>$\mu^+\mu^-$ Preselection</th>
<th>$\mu^+\mu^-$ Final selection</th>
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</thead>
<tbody>
<tr>
<td>$Z/\gamma^* \rightarrow e^+e^-$</td>
<td>274886</td>
<td>158 ± 13</td>
<td>373582</td>
<td>1247 ± 37</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \mu^+\mu^-$</td>
<td>1441</td>
<td>0.7 ± 0.1</td>
<td>2659</td>
<td>12.0 ± 0.7</td>
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<tr>
<td>$Z/\gamma^* \rightarrow \tau^+\tau^-$</td>
<td>159</td>
<td>47.0 ± 4.4</td>
<td>184</td>
<td>74.6 ± 6.8</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>308</td>
<td>122 ± 11</td>
<td>236</td>
<td>91.5 ± 6.5</td>
</tr>
<tr>
<td>$W + jets/\gamma$</td>
<td>202</td>
<td>73.9 ± 6.4</td>
<td>272</td>
<td>107 ± 9</td>
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<tr>
<td>$WW$</td>
<td>137</td>
<td>11.5 ± 1.0</td>
<td>171</td>
<td>21.5 ± 2.0</td>
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<tr>
<td>$WZ$</td>
<td>117</td>
<td>9.3 ± 0.9</td>
<td>147</td>
<td>18.0 ± 1.8</td>
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<tr>
<td>$ZZ$</td>
<td>1370</td>
<td>1.0 ± 0.1</td>
<td>408</td>
<td>53.8 ± 10.3</td>
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<tr>
<td>Multi-jet</td>
<td></td>
<td></td>
<td>377659</td>
<td>1625 ± 41</td>
</tr>
</tbody>
</table>

Signal ($m_H = 165$ GeV)
- $11.2\pm 7.2/0.8$
- $12.7\pm 9.0/1.0$

Total background
- $278620\pm 423/19$
- $377659\pm 1625/41$

Data
- $278277\pm 421$
- $384083\pm 1613$

$ee+\mu\mu$ 5.4 fb$^{-1}$

- $e\mu$ channel benefits from splitting in jet multiplicity bins
- For $e\mu$ ($m_H=165$ GeV)
  - $S/B \sim 13/2800$, $8/1100$, $5/600$
  - $S/\sqrt{B} \sim 0.24$, $0.24$, $0.20$

$e\mu$ 6.7 fb$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>Signal</th>
<th>Total Background</th>
<th>$Z \rightarrow ee$</th>
<th>$Z \rightarrow \mu\mu$</th>
<th>$Z \rightarrow \tau\tau$</th>
<th>$t\bar{t}$</th>
<th>$W + jets$</th>
<th>$WW$</th>
<th>$WZ$</th>
<th>$ZZ$</th>
<th>Multi-jet</th>
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<tr>
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<td></td>
<td>$e^\pm \mu^\mp$ channel</td>
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<tr>
<td>0 jets</td>
<td>2662</td>
<td>13.2</td>
<td>2838</td>
<td>8.9</td>
<td>172.2</td>
<td>1318</td>
<td>10.8</td>
<td>684.2</td>
<td>447.0</td>
<td>16.5</td>
<td>2.2</td>
<td>177.8</td>
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<tr>
<td>1 jet</td>
<td>1164</td>
<td>7.9</td>
<td>1132</td>
<td>4.8</td>
<td>40.6</td>
<td>585.5</td>
<td>107.6</td>
<td>147.6</td>
<td>99.0</td>
<td>6.5</td>
<td>1.6</td>
<td>138.4</td>
</tr>
<tr>
<td>$\geq 2$ jets</td>
<td>636</td>
<td>4.8</td>
<td>593.6</td>
<td>2.3</td>
<td>14.4</td>
<td>162.8</td>
<td>300.6</td>
<td>38.1</td>
<td>21.9</td>
<td>2.7</td>
<td>1.4</td>
<td>49.2</td>
</tr>
</tbody>
</table>
Last step: multivariate analysis

- MVA optimized for each sub-channel and mass hypothesis.
- Input variables: event topology, lepton kinematics, quality of leptons, jet content, relation between lepton and $E_T$, relation between jets and $E_T$.
- Output discriminant is the input for statistical analysis of data.

Splitting and dedicated training in different jet multiplicity bins to fight against different backgrounds.

Signal $\propto 10$ ($M_H = 165$ GeV)
Di-lepton + $E_T$: systematic uncertainties

- Flat systematics: affect overall normalization
- Shape systematics: modify output of final discriminant
- Impact of systematics is reduced thanks to profiling techniques (~fit procedure in background dominated region)

<table>
<thead>
<tr>
<th>Main systematics</th>
<th>Signal</th>
<th>Bkg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton id (flat)</td>
<td>3-6%</td>
<td>3-6%</td>
</tr>
<tr>
<td>Luminosity (flat)</td>
<td>6.1%</td>
<td>6.1%</td>
</tr>
<tr>
<td>Cross-section (flat)</td>
<td>11%</td>
<td>6-10%</td>
</tr>
<tr>
<td>$p_T(Z)$ $p_T(W)$</td>
<td>1.5%</td>
<td>1-5%</td>
</tr>
<tr>
<td>$p_T(WW)p_T(H)$</td>
<td>1.5%</td>
<td>1-5%</td>
</tr>
<tr>
<td>Jet modeling</td>
<td>1-18%</td>
<td>1-18%</td>
</tr>
<tr>
<td>Jet calibration</td>
<td>1-5%</td>
<td>1-5%</td>
</tr>
</tbody>
</table>

$m_H = 165$ GeV

PRL. 104, 061804 (2010)

ee+eµ+µµ
Di-lepton + $E_T$: results

Limits @95% CL in SM cross-section unit

For $m_H = 165$ GeV and 5.4 fb$^{-1}$

ee+μμ+μμ: $\sigma_{95}/\sigma$(SM) = 1.55 (1.36 expected)

For $m_H = 165$ GeV and 5.4 fb$^{-1}$

ee+μμ: $\sigma_{95}/\sigma$(SM) = 1.99 (1.93 expected)

For $m_H = 165$ GeV and 6.7 fb$^{-1}$

eμ only: $\sigma_{95}/\sigma$(SM) = 1.39 (1.62 expected)

expected sensitivity increased by ~18%
**Higgs search within 4th generation model**

- New heavy generation of quarks
  - ggH coupling is multiplied by 3 compared to SM
  - Production is enhanced by 9
- Search in di-lepton +MET channel can be recycled
  - Some analysis tuning required because of extended mass reach (eg $\Delta \phi(l,l)$ cut not applicable when W's are boosted)

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

**CDF+D0 combined exclusion:** $130 < m_H < 210$ GeV @95%CL (infinite mass scenario)
Like-sign leptons: signature and background

Signature:
- 2 isolated high $p_T$ leptons
- same charge
- Large missing $E_T$

Backgrounds
- Di-boson $WZ$, $ZZ$
- Drell-Yan $Z/\gamma$
  - mis-measurement of lepton charge (charge flip)
- $W$+jet
  - Jet mis-identified as lepton
- QCD multijet events
  - Jets mis-identified as leptons
Like-sign leptons: analysis strategy

- Split into ee, e\(\mu\), \(\mu\mu\), to increase sensitivity
  - Different Background composition
  - Different rate of jets faking lepton
  - Different charge mis-id rate

**Selection**

- 2 isolated leptons, \(p_T>15\) GeV, same charge
- High quality track to reduce charge flip bkg
- Reject events from background control region
  - \(85<M_{l1,l2}<100\) GeV, \(\Delta\phi(l1,l2)>2.8\)
  - \(30<M_{l1,l2}<50\) GeV, \(\Delta\phi(l1,l2)>2.5\)

**Last steps: multivariate analysis** (new compared to 3.6 fb\(^{-1}\) analysis)

- Decision Trees specifically trained against instrumental bkg
- Decision Trees specifically trained against W+jet and di-boson bkg
Like-sign leptons: backgrounds

- Determine instrumental background from data
  - charge flip:
    - $\mu\mu$ channel exploits redundancy between tracking and mu spectrometer
    - ee channel exploits Z-peak reconstructed by calorimetry
    - Charge mis-id rate from control region
    - Event kinematic from opposite sign data
- QCD multijet background
  - rate from background control region
  - QCD kinematic from inverting tight lepton criteria (isolation, em shower shape discriminant)

<table>
<thead>
<tr>
<th>Channel</th>
<th>ee</th>
<th>$\mu\mu$</th>
<th>$e\mu$</th>
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<tbody>
<tr>
<td>Background</td>
<td>12.0±1.5</td>
<td>17.2±3.3</td>
<td>24.1±2.6</td>
</tr>
<tr>
<td>Data</td>
<td>13</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>$m_H=160$ GeV</td>
<td>0.39</td>
<td>0.56</td>
<td>0.93</td>
</tr>
<tr>
<td>S/$\sqrt{B}$</td>
<td>0.11</td>
<td>0.14</td>
<td>0.19</td>
</tr>
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</table>
Like-sign leptons: results

- Final multivariate discriminants to derive limits
  - Exploit: Event topology, lepton kinematics, jet content, relation between lepton and $E_T$

Main systematic uncertainties
- 10-12% for acceptance
- 20% on W+jet background
- 20-150% on instrumental background

Limit for $m_H=165$ GeV and $5.4$ fb$^{-1}$: $\sigma_{95}/\sigma_{\text{SM}} = 7.2$ (7.0 expected)

expected sensitivity in 3.6 fb$^{-1}$ analysis was 10.5\sigma_{\text{SM}}$
lepton+jets: signature and background

- **Signature from** $WW \rightarrow l\nu qq$
  - 1 isolated high $p_T$ lepton
  - Large missing $E_T$
  - 2 jets

- **Selection:**
  - One isolated high $p_T$ (lepton)$>15$ GeV
  - 2 well reconstructed jets
  - Require $E_T > 15$ GeV, $M_T(W)+0.5\ E_T > 40$ GeV

- **Backgrounds**
  - Main background: $W+$ 2 jets
  
  - Top production
  - Di-boson $WW, WZ, ZZ$
  - QCD multijet events with jets identified as leptons
Large overwhelming W+jets background after selection

- \( S/\sqrt{B} \approx 0.22 \) (\( m_H = 165 \text{ GeV} \))

<table>
<thead>
<tr>
<th>Channel</th>
<th>( H \rightarrow WW )</th>
<th>( V+)jets</th>
<th>Multijet</th>
<th>top</th>
<th>( VV )</th>
<th>data</th>
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<td>52156</td>
<td>11453</td>
<td>2433</td>
<td>1585</td>
<td>67627</td>
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<td>muon</td>
<td>32.2</td>
<td>47201</td>
<td>2409</td>
<td>1598</td>
<td>1225</td>
<td>52433</td>
</tr>
</tbody>
</table>

Further discrimination needed with help of kinematic variables.
- Use W mass constraint to reconstruct neutrino \( p_Z \)
- Exploit full event kinematics and topology by means of Decision Trees
  - Trained separately for e and \( \mu \) channels and for each tested Higgs mass
lepton+jets: results

- Final multivariate (Random Forest) discriminants to derive limits

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<td>4%</td>
<td>4%</td>
</tr>
<tr>
<td>Luminosity (flat)</td>
<td>6.1%</td>
<td>6.1%</td>
</tr>
<tr>
<td>Cross-section (flat)</td>
<td>10%</td>
<td>6-10%</td>
</tr>
<tr>
<td>Jet calibration and resolution</td>
<td>5%</td>
<td>4-7%</td>
</tr>
</tbody>
</table>

\[ e \nu jj + \mu \nu jj: 5.4 \text{ fb}^{-1} \]

**Limit for** \( m_H = 165 \text{ GeV} \) \( \sigma_{95} / \sigma(\text{SM}) = 3.8 \) (5.5 expected)
Conclusions

- Search for Standard Model high mass Higgs at D0
  - 2 channels: updated samples and improved analysis techniques
  - 1 channel completely new
  - Sensitivity improves faster than $\sqrt{L}$
- The results need to be combined to reach sensitivity to SM Higgs
  - Dzero combination: M. Mulhearn's talk tomorrow
  - Tevatron combination: B. Kilminster's talk on Monday
- Many improvements foreseen for near future
  - More data, more efficiency, more channels
- Exciting times ahead

...ICHEP 2010
..later this week..
Support slides
Many improvements are foreseen for near future
- More than 10 fb\(^{-1}\) by the end of 2011
- More optimized lepton id criteria
  - already in WW → e\(\mu\) ~+15%
- Increased lepton acceptance
  - already +15% in ZH → eebb
- New channels
  - WW → e + tau, WW → mu + tau
  - tri-lepton signatures (from HW → WWW and H → ZZ)
- Reduced systematic uncertainties
- Better multivariate techniques

Most of these improvements will also extend reach of « high mass » channels toward lower mass
- On the verge of being sensitive to Higgs production with D0 only data
- Exciting times ahead
The D0 Experiments at RunII

- New in RunII
  - Tracking in B-field
  - Silicon detector
  - fiber tracker

- Upgraded for Run II
  - Calorimeter,
  - muon system
  - DAQ/trigger

- RunIIb (2006):
  - Silicon layer 0
  - Cal Trigger

- Typical coverage
  - Muons $\eta < 2$
  - Electrons
    - $\eta < 1.1$
    - $1.5 < \eta < 2.5$
  - Jets $\eta < 2.5$
D0+CDF combined results

First D0+CDF joint publication on Higgs search.


Exclusion 162-166 GeV @95CL
(Expected sensitivity for exclusion 159-169 GeV)
At low mass Prob < 30%.
Need to be somewhat lucky to see low mass Higgs.
separation between $LLR_b$ and $LLR_{s+b}$ give the power to exclude or discover a Higgs
Luminosity prospects

For data analysis
~10 fb⁻¹ expected by the end of 2011

Real data for FY02-FY09

The green line assumes the same rate for delivered luminosity as in FY09, 50 pb⁻¹/week
WW and WZ signal in lepton+jet channels

With 1.1 fb$^{-1}$, D0 saw evidence at 4.4 $\sigma$ for W(W/Z) production in the (W$\rightarrow$l$\nu$)(W/Z$\rightarrow$jj) channel

Phys. Rev. Lett. 102 , 161801 (2009 )
Evolution of sensitivity

Tevatron Run II Preliminary
Expected Limits

95% CL Limit / SM

Standard Model = 1.0

m_H (GeV/c^2)

Summer 2006
Fall 2007
Winter 2008
Summer 2008
Winter 2009
Fall 2009