Search for the SM Scalar Boson at low mass with secondary channels at the Tevatron

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On behalf of the CDF and DØ Collaborations

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Low Mass Higgs Boson

- EW fits predict $m_H < 152$ GeV
- $\sim 5$ s.d. excess at 125 GeV at LHC
- 2.9 s.d. excess at Tevatron
The Tevatron

- Shut down in September 2011
- $p\bar{p}$ collider with 1.96 TeV c.o.m. energy
- Peak Luminosity $4 \times 10^{32}$ cm$^{-2}$s$^{-1}$
- Delivered 12 fb$^{-1}$ to each experiment
The Tevatron

- Both detectors operated at >90% efficiency
  - Each recorded over 10 fb\(^{-1}\) of data
Higgs Boson Production at the Tevatron

\[ \sigma(p\bar{p}) \] (pb)

- $gg \rightarrow H$
- $qq \rightarrow Hqq$
- $qq \rightarrow HW$
- $qq \rightarrow HZ$
- $gg, q\bar{q} \rightarrow Htt$
- $gg, q\bar{q} \rightarrow Hbb$

$M_H$ (GeV)
Low Mass Higgs Boson Decays

Primary
- WH→ℓνbb
- ZH→ννbb
- ZH→ℓℓbb

Secondary
- VH→qqbb
- Htt→bb + jets
- H→ττ + jets
- H→ττ + leptons
- XH→μττ
- H→γγ + jets
\[ H \rightarrow \gamma\gamma \]
CDF H → γγ

- Scan γγ mass spectrum in 10 fb⁻¹ of data
- Require 2 photons – at least 1 in central region
  - Include γ→ee candidates in sub-channels
- Identify central (plug) photons with NN (cuts)
- Simulated Higgs boson mass resolution of 3 GeV

10 fb⁻¹
CDF $H \rightarrow \gamma\gamma$

- Di-photon mass is final discriminant
- Estimate background by fitting to data
  - Remove 12 GeV mass window around each mass hypothesis for fit
- Observed (expected) confidence limit at 125 GeV: $12.2 (10.8) \times \text{SM } \sigma$
**DØ H → γγ**

- **Require 2 central photons**
  - Identified using NN and selection cuts
  - Use central preshower detector to verify vertex

- **Drell-Yan, γ-jet/jet-jet and direct γγ backgrounds**
  - Simulate Drell-Yan
  - Data driven method for other backgrounds

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**DØ preliminary, 9.7 fb⁻¹**

- **Z → l⁺l⁻γ (l=e,μ) data**
  - γ MC
  - jet MC

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**DØ preliminary, 9.7 fb⁻¹**

- Data
  - γγ
  - γ+jet
  - jet+jet
  - Z/γ⁺⁺→ ee
  - signalx100 (M_H = 125 GeV)
- Divide into γ- and j-dominated regions
- BDT trained to identify signal-like events

- Observed (expected) confidence limit is 12.9 (8.2) x SM σ at 125 GeV
Tevatron $H \rightarrow \gamma\gamma$ Combination

- Combined limit $\sim 10 \times \text{SM } \sigma$ at 125 GeV
- Expected limit is $\sim 6 \times \text{SM } \sigma$
$H \rightarrow \tau\tau$
CDF $H \rightarrow \tau\tau + \text{Jets}$

- **Search for Higgs bosons from four processes:** WH, ZH, VBF and GF
  - Majority of signal events include 1 or more jets

- **Final states** $\tau_{h} + e/\mu$ or $e+\mu$, +1 or more jet

- **Major backgrounds:** jet $\rightarrow \tau$, $Z \rightarrow \tau\tau$, $tt$

$8.3 \text{ fb}^{-1}$
CDF $H \rightarrow \tau\tau + \text{Jets}$

- Use Support Vector Machine (SVM) to boost sensitivity (one SVM per bkgd. per channel)
- Observed (expected) cross section limit is $11.7 (14.8)$ times SM at 125 GeV
CDF $H \rightarrow \tau\tau + \text{Leptons}$

- Complement $H \rightarrow \tau\tau + \text{jets}$ search
  - $VH \rightarrow ll \ \tau\tau$ is main signal
- Large Drell-Yan background suppressed using SVM
- Exclude cross section $26.5 \times$ SM prediction (exp. 23.3) at 125 GeV

$6.2 \text{ fb}^{-1}$
DØ H → ττ

- Search for $\tau_h + e/\mu + \text{jets}$, and $\tau_h + \mu$
- Separate MVA for each channel
- Observed limit 15.7 x SM prediction for $m_H = 125$ GeV (exp. limit 12.8)
DØ μττ + jets

- Sensitive to $H \rightarrow V V$, $H \rightarrow \tau \tau$, $H \rightarrow \mu \mu$
- Backgrounds: $Z \rightarrow l l$, diboson, multi-jet
- Use reconstructed Higgs $p_T$ as final variable
- Observed limit is $13.1 \times \text{SM } \sigma$ (17.6 expected)

$7.0 \text{ fb}^{-1}$
$H \rightarrow bb$
H → bb

- Extremely rewarding – and challenging – analysis channel
- Use associated products to suppress MJ
CDF Htt $\rightarrow$ bb + jets + X

- Search for two b-jets + top decay products
- Very large tt background: train NN to identify signal events
- Multiple jet pairs: combine di-jet masses in NN

9.45 fb$^{-1}$
CDF Htt→bb + jets + X

- NN response used to set cross-section limits

- Observed limit is 17.6 times SM Higgs cross section at 125 GeV (12.36 expected)
CDF (V/qq) H → qqbb

- All-hadronic final state
  - b-tagging and jet width measurement reduce bkg.
- NN's suppress background
CDF (V/qq) H → qqbb

- Super-Discriminant trained on response of WH, ZH and VBF NN's
- Observed (expected) cross section limit is 9.0 (11.0) x SM
## Summary of Results

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limit at 115 GeV</th>
<th>Limit at 125 GeV</th>
<th>Data Analysed</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Obs.</td>
<td>Exp.</td>
<td>Obs.</td>
</tr>
<tr>
<td>CDF $H \rightarrow \gamma\gamma$</td>
<td>12.7</td>
<td>10.6</td>
<td>12.2</td>
</tr>
<tr>
<td>DØ $H \rightarrow \gamma\gamma$</td>
<td>7.9</td>
<td>9.7</td>
<td>12.9</td>
</tr>
<tr>
<td>CDF $H \rightarrow \tau\tau$+jets</td>
<td>12.2</td>
<td>12.6</td>
<td>11.7</td>
</tr>
<tr>
<td>CDF $H \rightarrow \tau\tau$+ll</td>
<td>18.5</td>
<td>17.3</td>
<td>26.5</td>
</tr>
<tr>
<td>DØ $H \rightarrow \tau\tau$</td>
<td>21.8</td>
<td>14.3</td>
<td>15.7</td>
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<tr>
<td>DØ $\mu\tau\tau$</td>
<td>10.7</td>
<td>14.2</td>
<td>13.1</td>
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<tr>
<td>CDF $ttH \rightarrow ttbb$</td>
<td>14.5</td>
<td>10.1</td>
<td>17.6</td>
</tr>
<tr>
<td>CDF VH$ \rightarrow qqbb$</td>
<td>7.2</td>
<td>8.3</td>
<td>9.0</td>
</tr>
</tbody>
</table>
Conclusion

• Secondary channels sensitive to $\sim 10 \times \text{SM } \sigma$
  – Included in Tevatron Higgs combination
  – Provide comparison with LHC

• Many thanks to everyone at Fermilab for the great results!

Primary channels VH $\ell\ell bb$, $\ell\nu bb$, $vv bb$ coming next – stay tuned!
Additional Slides
Further Information:

- CDF Higgs Results:
  - www-cdf.fnal.gov/physics/new/hdg/Results.html

- DØ Higgs Results:
  - www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm

- Tevatron New Phenomena & Higgs Working Group:
  - http://tevnphwg.fnal.gov/
Higgs Cross-Section at Tevatron

\[ \sigma_H = 500 \text{ GeV} \]

\[ 1 \text{ pb} \]
Tevatron Performance

![Graph showing Tevatron Performance](image-url)

- Delivered to tape
- Month 4, 7, 10, 14, 17, 20, 23
- Total Luminosity (pb^{-1})
- Store Number

![Graph showing Run II Integrated Luminosity](image-url)

- Delivered
- Recorded
- Run II Integrated Luminosity
- 19 April 2002 - 30 September 2011
- Luminosity (fb^{-1})
- 11.9
- 10.7
Tevatron Performance

CDE Acquired Luminosity (pb\(^{-1}\))

Collider Run II Peak Luminosity

- Peak Luminosity
- Peak Luminosity 20x Average

Day

Date
Photon ID

- CDF NN inputs
  - $E_{EM}/E_{Had}$
  - Calo isolation
  - Tracker isolation
  - Shower profile $\chi^2$
- DØ NN inputs
  - Track $p_T$ sum
  - Calo isolation
  - # CPS clusters
  - CPS deposit width
- Trained on $\gamma$ & j MC in both cases
- Certified on $Z \rightarrow ll+j$ events
Tau ID

- **3 types of Hadronic tau candidate**
  - 1: $\tau \rightarrow \pi^\pm \nu$
  - 2: $\tau \rightarrow \pi^\pm \pi^0 \nu$
  - 3: $\tau \rightarrow \pi^\pm \pi^\mp \pi^\pm \pi^0 \nu$
- **CDF: suite of BDTs**
  - Divided by # tracks
  - And by visible $P_T$
- **DØ: one NN for each $\tau$ type**
b-jet ID

- b-jets have longer life time than light jets
- Several parameters indicate heavy jet:
  - Secondary vertex
  - Impact parameter
  - Soft lepton
- CDF and DØ input these variables into MVA
CDF $H \rightarrow \gamma \gamma$: Expected Sensitivity

- $H \rightarrow \gamma \gamma$ mass peak scaled by cross-section limit: CDF sensitive to excess this size
CDF VH→qqbb: MJ Background

Define control regions to estimate MJ in signal region ↓

↑ MJ in 2 tag channel ~ scaled version of 1 tag channel
NN and BDT

- Nodes represent linear/sigmoid functions
- Neuron weights altered to give output = target
- Cuts increase purity
- Combine many trees: weight difficult-to-identify events higher
Support Vector Machine

- Events are vectors in multi-dimensional hyperplane
- Define a separating plane using minimal set of vectors (*support vectors*)
- Move plane to maximise margin between plane and support vectors