Standard Model Higgs boson searches in challenging channels using the full CDF dataset

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on behalf of CDF collaboration

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Tevatron and CDF

- \( \bar{p}p \) collider, \( \sqrt{s} = 1.96 \text{ TeV} \), \( L_{\text{peak}} = 4.3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \)
- \( \sim 12 \text{ fb}^{-1} \) delivered before shut down, Sept 2011, \( \sim 10 \text{ fb}^{-1} \) collected
- Analyses presented today: \( 8.3 \text{ fb}^{-1} < \int L < 10 \text{ fb}^{-1} \)
Higgs Production at the Tevatron

\[ \sqrt{s} = 1.96 \text{ TeV} \]

\[ \sqrt{s} = 8 \text{ TeV} \]

**\( \bar{p}p \) versus \( pp \) → different relative contribution of production mechanisms**

<table>
<thead>
<tr>
<th>Production Mechanism</th>
<th>Tevatron</th>
<th>8 TeV LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{ggH} ) - gluon fusion</td>
<td>0.95 pb</td>
<td>19.52 pb</td>
</tr>
<tr>
<td>( \sigma_{VH} ) - associated production</td>
<td>0.21 pb</td>
<td>1.09 pb</td>
</tr>
<tr>
<td>( \sigma_{VBF} ) - vector boson fusion</td>
<td>0.07 pb</td>
<td>1.56 pb</td>
</tr>
</tbody>
</table>

\[ m_H = 125 \text{ GeV}/c^2 \]
Higgs search strategy at the Tevatron

\[ \sigma (ggH) \cdot B.R. \ (H \rightarrow b\bar{b}) \sim 0.5 \text{ pb} \]
- overwhelmed by QCD

\[ \sigma(VH) \cdot B.R. \ (H \rightarrow b\bar{b}) \sim 0.1 \text{ pb} \]
- leptons from W/Z decays help to reduce background

\[ \rightarrow \text{Associated production: main low mass channel} \]

Signal from background separation is challenging
inelastic cross section \( \sim 70 \text{ mb} \)

Strategy:
- Search in many optimized channels
- Combine channels to achieve best sensitivity
Higgs search strategy at the Tevatron

More Challenging Channels:
- Expected limit $> 10 \sigma_{S.M}$
- Combined limit $> \sim 5 \sigma_{S.M}$

Primary Channels:
- $H \rightarrow b\bar{b}$
- Associated VH production
- Expected limit $\sim 1.5 - 2 \sigma_{S.M}$
Search for $H \rightarrow \gamma\gamma$

- Search for a narrow resonance on a continuous background

**Advantages:**
- Mass resolution: $\sim 3$ GeV
- Include ggH, VH and VBF
- Sensitivity $\sim$ constant over a wide mass range

**Challenge:**
- $\text{max B.R. (}H \rightarrow \gamma\gamma) = 0.2\%$ at $m_H = 120$ GeV/c$^2$
  - $\rightarrow$ maximize acceptance

**Photon ID:**
Central Photon (C): $|\eta| < 1.05$, use NN trained to reduce $\pi/\eta$ faking $\gamma$
Forward Photon (P): $1.2 < |\eta| < 2.8$, cut based ID
Central Conversion (C'): use electrons from $\gamma$ conversion

**Data split in 4 channels:** CC, CP, CC', C'P
**H → γγ Signal and Background modeling**

**Signal:** PYTHIA MC

**Background:**
Prompt photons production + fakes photons

**Background Modelling:**
- Fit to sidebands of signal region
  
  **Signal region:** 12 GeV window centered at $m_H$ to be tested
  
  **Fit function:** sum of two exponentials multiplied by fraction-degree polynomial
  
  add Breit-Wigner function to model Z (only P)

- Extrapolate fit into signal region → background yield
  
  fluctuate parameters of the fit to estimate background rate uncertainty in signal region:
  
  2.8% (CC) - 6.1% (CP)
Result for $H \rightarrow \gamma\gamma$ search

Limit at $m_H = 125$ GeV/c$^2$

$\text{Obs (Exp)} = 12.2(10.8) \sigma_{\text{S.M.}}$

Signal at $m_H = 115$ GeV/c$^2$

Scaled by expected limit: $10.6 \sigma_{\text{S.M.}}$
Search for $H \rightarrow \tau \tau + \text{jets}$

- At low masses $\text{BR}(H \rightarrow \tau \tau) \sim 10\%$
- Many decay modes, only two explored:
  - $e \backslash \mu + \tau_{\text{had}}$ (BR: 46%)
  - $e + \mu$ (BR: 3%)

### Event Selection:

<table>
<thead>
<tr>
<th>$e \backslash \mu + \tau_{\text{had}}$</th>
<th>$e + \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e \backslash \mu \ p_T \geq 10 \ \text{GeV/c}$</td>
<td>$e \ p_T \geq 10 \ \text{GeV/c}$</td>
</tr>
<tr>
<td>$\tau_{\text{had}} p_T \geq 15(20) \ \text{GeV/c}$</td>
<td>$\mu \ p_T \geq 10 \ \text{GeV/c}$</td>
</tr>
<tr>
<td>Opposite Charge</td>
<td>Opposite Charge</td>
</tr>
<tr>
<td>$\geq 1$ jet</td>
<td>$\geq 1$ jet</td>
</tr>
</tbody>
</table>

Classify events by numbers of jet:

<table>
<thead>
<tr>
<th>$e \backslash \mu + \tau_{\text{had}}$</th>
<th>$e + \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 jet</td>
<td>2 jets</td>
</tr>
<tr>
<td>1 jet</td>
<td>2 jets</td>
</tr>
<tr>
<td>$\sigma_{ggH}$</td>
<td>$\sigma_{VH}$</td>
</tr>
<tr>
<td>72.6%</td>
<td>58.4%</td>
</tr>
<tr>
<td>33.5%</td>
<td>32.2%</td>
</tr>
<tr>
<td>21.7%</td>
<td>48.8%</td>
</tr>
<tr>
<td>36.9%</td>
<td>52.2%</td>
</tr>
</tbody>
</table>
Background Estimation

- Main background $Z/\gamma^* \rightarrow \tau\tau$: ALPGEN MC
  $Z/\gamma^* \rightarrow ee/\mu\mu$, top, di-boson : MC

- MultiJet background: Same Sign data events

- W+jets:
  included in SS sample
  because of charge correlation, $N_{OS} > N_{SS}$
  \rightarrow correct for excess of W+jets OS events

Test background modeling in 0 jet bin
➢ Signal peak on top of Drell-Yan background neutrinos and detector resolution broaden Z and Higgs mass distribution → Z/H peaks not distinguishable

➢ Use multivariate technique (Support Vector Machine)
  - train a different SVM to separate each individual background process from signal
  - final discriminant: minimum value in any SVM classifier
Result for $H \rightarrow \tau \tau + \text{jets}$ search

Limit at $m_H = 125 \text{ GeV}/c^2$

$\text{Obs (Exp)} = 11.7(14.8) \sigma_{\text{S.M.}}$
Search for $H \rightarrow ZZ^{(*)} \rightarrow 4$ leptons

- Clean channel but small signal rate
- Two same flavor/opposite charged pairs of isolated leptons
  - $P_T > 20$ GeV/c (triggering lepton)
  - $P_T > 10$ GeV/c (other leptons)
  - no cut on $M_{ll}$
- Include ZH production, $H \rightarrow WW/\tau\tau$
  ~ double signal yield
- Backgrounds:
  - non-resonant $ZZ^{(*)}$ SM : PYTHIA MC
  - $Z\gamma + \text{jets}/Z+2\text{jets}$: data-driven estimate
  shape from Bauer MC

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZZ$</td>
<td>10.59 ± 1.34</td>
</tr>
<tr>
<td>Fakes</td>
<td>0.39 ± 0.19</td>
</tr>
<tr>
<td>Total Background</td>
<td>10.98 ± 1.34</td>
</tr>
</tbody>
</table>

CDF Run II Preliminary $\int \mathcal{L} = 9.7$ fb$^{-1}$

<table>
<thead>
<tr>
<th>Higgs Process $m_H = 130$ GeV/c$^2$</th>
<th>Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H \rightarrow ZZ$</td>
<td>0.09</td>
</tr>
<tr>
<td>$WH \rightarrow WZZ$</td>
<td>0.01</td>
</tr>
<tr>
<td>$ZH \rightarrow ZZZ$</td>
<td>0.01</td>
</tr>
<tr>
<td>$VBF \ H \rightarrow ZZ$</td>
<td>0.01</td>
</tr>
<tr>
<td>$ZH \rightarrow ZWW$</td>
<td>0.07</td>
</tr>
<tr>
<td>$ZH \rightarrow Z\tau\tau$</td>
<td>0.03</td>
</tr>
<tr>
<td>Data</td>
<td>9</td>
</tr>
</tbody>
</table>
Result for $H \rightarrow H \rightarrow ZZ^(*) \rightarrow 4$ leptons

Discriminant: distribution in $M_{4l}$-MET plane
- no real MET in $H \rightarrow ZZ$ events
- real MET in $ZH \rightarrow ZWW \rightarrow ll lv lv$

→ improve limit by 10-15 %

Search performed for $120 < m_H < 300 \text{ GeV/c}^2$

Limit at $m_H = 130 \text{ GeV/c}^2$

Obs $(\text{Exp}) = 20.5 \ (18.3) \sigma_{S.M.}$
Search for ttH production: lepton + jets

- $\sigma(ttH) = 4.3\text{ fb (} m_H = 125 \text{ GeV/c}^2)$

- Include all hadronic decays of the Higgs $H \rightarrow b\bar{b}$, $H \rightarrow WW$, $H \rightarrow \tau\tau$

- Event Selection:
  - $e/\mu$ with $p_T > 20 \text{ GeV/c}$
  - at least 4 jets ($E_T > 20 \text{ GeV} |\eta| < 2.0$)
  - at least 2 b-quarks in final state

- Pure sample of $t\bar{t}$
Search for $ttH$ production: lepton + jets

- $\sigma(ttH) = 4.3$ fb ($m_H = 125$ GeV/c$^2$)

- Include all hadronic decays of the Higgs $H \to b\bar{b}$, $H \to WW$, $H \to \tau\tau$

- Event Selection:
  - $e/\mu$ with $P_T > 20$ GeV/c
  - at least 4 jets ($E_T > 20$ GeV, $|\eta| < 2.0$)
  - at least 2 b-quarks in final state

- Pure sample of $t\bar{t}$

- Classify events by:
  - number of jets: 4, 5, $\geq 6$ jets
  - number of b-tagged jets: 2 or $\geq 3$
Results for ttH production: lepton + jets

- Neural Network discriminant:
  - one for event category

Limit at $m_H = 125 \text{ GeV}/c^2$

Obs (Exp) = $17.6 (12.36) \sigma_{\text{S.M.}}$

NN trained only for one mass point
  → very smooth limit
Presented the status of $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow \tau\tau + \text{jet}$ and $ttH$ at CDF

Challenging channels contribute to the overall CDF sensitivity:
- combined expected sensitivity comparable to one of the main analyses

Tevatron experiments pioneered these channels:
  - first data analyses back into 2008-2010

4th of July:
  - ATLAS and CMS discovered a new particle in $\gamma\gamma$ and $ZZ$ final states
  - $m \sim 125-126$ GeV/c²

→ Measure its properties to determine its nature (is it really a Higgs boson?)

Tevatron results still matter:
  - currently provide a unique window in $H \rightarrow b\bar{b}$ modes
  → see Wei-Ming Yao and Satish Desai talks this afternoon