Search for the Standard Model Higgs Boson
Produced in Association with a W boson at CDF

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On behalf of the
Collider Detector at Fermilab
WH Working Group

Higgs Hunting Workshop, Orsay, 2011

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Want to perform a low mass SM Higg search

Our search: a W boson + a Higgs boson

The W boson decays to an electron (muon) + neutrino

It helps us a lot that we can identify well electrons and muons in the detector

Our search (WH)

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Event Selection

- One charged lepton, large missing transverse energy and two jets, out of which at least one originates from a bottom quark
- Also includes ZH → llbb, where one lepton is missed
- 4 charged lepton categories
  - Triggered central tight leptons, forward tight electrons
  - Non triggered loose electrons and muons (MET+ jets triggers)
- Pretag used as control region
- 4 orthogonal b-tagging categories as signal regions
Improvements Since 2010

- **Increased the integrated luminosity** from 5.7 to 7.5 fb⁻¹

- **Improvements on the non-W QCD background**
  - Replaced the cut-based non-W QCD veto with a better multivariate technique, which reduces the contribution of this background and increases the signal – see F. Sforza’s talk
  - Improved the model for the central for the central electrons
  - Relaxed the MET cut for the central muons

- **Improvements on signal acceptance**
  - Increased acceptance for the non triggered loose muons through the addition of a third MET+jets trigger thanks to a novel in trigger combination method - next slide and backup slides
  - Increased acceptance for the non triggered loose electrons through the use of the high-p_T electron triggers
New Trigger Combination Method To Avoid a Logical OR

- Consider each event its own kinematic region.
- Equivalent to dividing the kinematic phase space in an infinity of mutually orthogonal kinematic regions.
- No more need to study and identify before the analysis all the orthogonal kinematic regions.
- On an event-by-event basis, the trigger with largest a priori probability to fire is chosen *(in-situ trigger study)*, the probability being the product of:
  - Trigger probability to fire each trigger level based on trigger parameterization (trigger MET, jet kinematic quantities).
  - Inverse of the trigger prescale for the event (ex: 0.91).
  - 0 or 1 (if the trigger is defined or not for the event).
    - For MC, a random number simulates in which data period it is.
  - 0 or 1 (if the trigger-specific jet event selection is passed).
Final Discriminant

- Inputs: dijet invariant mass + other kinematic quantities
- Backgrounds (signal) peak to the left (right)
- Good agreement between data and background
- No excess seen, so we continue to set limits

Central Lepton 2 b-tagged jets

2JET

WH→lνb¯b

CDF Run II Preliminary (7.5 fb⁻¹)

- Diboson
- QCD
- Top
- WH115
- Wjets
- ZH115
- Zjets

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Limit Setting & Systematic Uncertainties

- **Bayesian** approach with **Poisson** statistics and **flat priors**

- Rate and shape systematic uncertainties are introduced as **nuisance parameters**
  - Truncated Gaussian distributions

- **Rate**: uncertainty on the total normalizations
- **Shape**: uncertainty on bin-by-bin normalizations
  - Use full discriminant shapes to extract the most information

- **Correlated** among various channels
WH Upper Limits

115 GeV/c²: observed (expected) upper limits at 95% CL
3.64 (2.78) x SM 2.65 (2.60) x SM

Most sensitive analysis in the world for low mass Higgs
WH Search Projection

- Always improved more than just by adding luminosity
- Band: conservative and optimistic improvement plan
Conclusion

- **WH Search, CDF Collaboration**
  - 2 jets: 7.5 fb\(^{-1}\), 3 jets: 5.6 fb\(^{-1}\)
  - Pretag sample as control region
  - 4 orthogonal b-tagging categories as signal regions
  - 4 orthogonal charged lepton categories

- **Heavy use of multivariate techniques**

- **No excess is seen, so we set 95% CL upper limits**
  - in the range 100 to 150 GeV/c\(^2\) with 5 GeV/c\(^2\) increments

- **Observed (Expected)**
  - from 1.12 (1.79)xSM for 100 GeV/c\(^2\) to 34.4 (21.6)xSM for 150 GeV/c\(^2\)
  - 2.65 (2.60) x SM at 115 GeV/c\(^2\)
  - Most sensitive analysis in the world for low mass Higgs!

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Backup Slides
The Higgs Boson

- **Motivation**
  - The only elementary particle predicted by the Standard Model not yet observed or refuted
  - Predicted by the Higgs mechanism in 1964, which explains
    - the spontaneous symmetry breaking
    - the masses of the electroweak bosons, the masses of fermions

- **The Higgs boson characterized only by its mass**
  - LEP direct searches
    - exclude masses < 114.4 GeV/c² at 95% CL
  - Previous Tevatron direct searches
    - exclude masses in [158-173] GeV/c² at 95% CL as of July 1st 2011
  - Indirect electroweak fits
    - exclude masses > 185 GeV/c² at 95% CL

- **Higgs production is a very rare process**

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## Event Yield Table

### $WH \rightarrow \ell vbb$, 2jets
CDF Run II Preliminary 7.5 fb$^{-1}$

<table>
<thead>
<tr>
<th>Source</th>
<th>ST+ST</th>
<th>ST+JP</th>
<th>ST+NN</th>
<th>1-ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>184050</td>
<td>184050</td>
<td>184050</td>
<td>184050</td>
</tr>
<tr>
<td>Pretag Events</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>142±22</td>
<td>114±12</td>
<td>62.8±6.4</td>
<td>479±49</td>
</tr>
<tr>
<td>Single top(s-ch)</td>
<td>45.0±6.7</td>
<td>35.1±3.4</td>
<td>18.9±1.8</td>
<td>106±10</td>
</tr>
<tr>
<td>Single top(t-ch)</td>
<td>13.9±2.4</td>
<td>13.3±2.0</td>
<td>8.7±1.2</td>
<td>191±23</td>
</tr>
<tr>
<td>WW</td>
<td>1.67±0.42</td>
<td>6.23±2.08</td>
<td>5.14±1.35</td>
<td>186±25</td>
</tr>
<tr>
<td>WZ</td>
<td>12.9±2.0</td>
<td>10.7±1.2</td>
<td>5.84±0.62</td>
<td>53.3±6.2</td>
</tr>
<tr>
<td>ZZ</td>
<td>0.62±0.09</td>
<td>0.49±0.06</td>
<td>0.29±0.03</td>
<td>2.05±0.23</td>
</tr>
<tr>
<td>$Z + jets$</td>
<td>9.64±1.40</td>
<td>11.9±1.7</td>
<td>8.75±1.30</td>
<td>182±25</td>
</tr>
<tr>
<td>$W\bar{b}$</td>
<td>257±104</td>
<td>228±91</td>
<td>125±50</td>
<td>1450±580</td>
</tr>
<tr>
<td>$Wc\bar{c}/c$</td>
<td>31.0±12.6</td>
<td>98.3±40.5</td>
<td>63.8±26.0</td>
<td>1761±708</td>
</tr>
<tr>
<td>Mistag</td>
<td>12.1±2.9</td>
<td>52.8±15.2</td>
<td>57.0±14.3</td>
<td>1646±220</td>
</tr>
<tr>
<td>non-W QCD</td>
<td>57.9±23.6</td>
<td>85.3±34.1</td>
<td>74.9±29.9</td>
<td>747±299</td>
</tr>
</tbody>
</table>

| Total background        | 584±169 | 656±194 | 432±126 | 6802±1822 |
| Observed Events         | 519     | 568     | 402     | 6482     |

WH and ZH signal (115 GeV)  7.28±0.98  5.34±0.39  2.80±0.19  16.0±1.2
Acceptance Improvement

Charged lepton (Electron or Muon)

Our contribution to improve the search:

More charged leptons, which means

More W bosons, which means

More WH events, which means

More signal selected, which means

Better Higgs sensitivity!

We introduce a new method to reconstruct electrons and muons that would normally be lost in the non instrumented regions of the detector.

WH Search at CDF, Higgs Hunting, Orsay, 2011

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Charged Lepton Improvement

Cylindrical detector rolled on a plane

Y axis: 0-2Pi
X axis – 0 for half height

Dark blue, Green – muons
Light blue – electrons
Red – muons or electrons that would be lost in the non instrumented regions of the detector, but we recover

WH Search at CDF, Higgs Hunting, Orsay, 2011
3 MET + jets triggers at CDF

- Not all triggers are defined for all runs
- A trigger had a bug for certain runs, must be treated as not defined
- Some triggers have prescales for certain data periods
- Used for non-triggered loose muon and electron candidates
- **How to combine the three triggers optimally while avoiding correlations as in the case of a logical OR between triggers, which brings extra systematic uncertainties, which are also harder to compute?**
Old Trigger Combination Method To Avoid a Logical OR

- Divide kinematic phase space in orthogonal regions
  - For many triggers, many kinematic regions
  - How to choose them? Study that before the analysis
  - Parameterize each trigger (at each level) in each region
    - Only this step will be generalized by the new method
- Assign only one trigger to all events in that region
- For MC events, assign an event weight between 0 and 1 as the probability that the trigger fires
- For data events, check if the trigger fired, if yes, return a weight of 1, if not, return a weight of 0 (reject event)
- For both MC and data, do not check the other triggers
  - To ensure orthogonality between triggers
New Trigger Combination Method To Avoid a Logical OR

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- On an event-by-event basis, the trigger with largest a priori probability to fire is chosen (in-situ trigger study), the probability being the product of
  - Trigger probability to fire each trigger level based on trigger parameterization (trigger MET, jet kinematic quantities)
  - Inverse of the trigger prescale for the event (ex: 0.91)
  - 0 or 1 (if the trigger is defined or not for the event)
    - For MC, a random number simulates in which data period it is
  - 0 or 1 (if the trigger-specific jet event selection is passed)
The novel method allows to add new charged lepton categories (non triggered loose muons and non triggered loose electrons)
  - These lepton candidates are isolated tracks that point to non instrumented regions of the detector
  - At CDF we do not have isolated track triggers
  - Use orthogonal trigger information, so MET+jets triggers
  - We have 3 of such triggers

This increases the signal acceptance by 50% over triggered tight charged leptons only (central electrons, central muons, forward electrons)

This increases the WH search sensitivity
Low Mass Searches

- Masses smaller than 135 GeV/c^2
- Higgs decays mostly to bottom quark pairs
- Single Higgs production (gluon fusion)
  - Largest cross section
  - Not feasible for bottom quark decay: 10^9 more QCD background
  - Still, use it for Higgs decays to photon or tau lepton pairs

- Associated production (WH, ZH, ttH)
  - Take advantage of the leptonic decays of the W or Z bosons
  - Charged-lepton and missing-transverse-energy based triggers
  - Identify jets that originate from bottom quarks

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Example of Discriminant

- WH → lvbb search 2jet b-tagging category with best s/b ratio; all charged leptons combined
- Artificial neural network as final discriminant trained for a Higgs boson mass of 115 GeV/c²
**Statistical Approach**

**Bayesian Posterior Probability**

\[
p(R|\bar{n}) = \frac{\int \int d\bar{s}d\bar{b}L(R, \bar{s}, \bar{b}|\bar{n})\pi(R, \bar{s}, \bar{b})}{\int \int \int dRd\bar{s}d\bar{b}L(R, \bar{s}, \bar{b}|\bar{n})\pi(R, \bar{s}, \bar{b})} \Rightarrow \int_0^{R_{0.95}} p(R|\bar{n})dR = 0.95
\]

\[
R = (\sigma \times BR)/(\sigma_{SM} \times BR_{SM}), \quad R_{0.95} : 95\% Credible Level Upper Limit
\]

\[
\bar{s}, \bar{b}, \bar{n} = s_{ij}, b_{ij}, n_{ij} (# \text{ of signal, background and observed events in } j\text{-th bin for } i\text{-th channel})
\]

\[
\pi : \text{Bayes' prior density}
\]

**Combined Binned Poisson Likelihood**

\[
L(R, \bar{s}, \bar{b}|\bar{n}) = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bin}}} \frac{\mu_{ij}^n e^{-\mu_{ij}}}{n_{ij}!}
\]

**Principle of ignorance**

- for the number of higgs events (instead of higgs Xsec)

\[
\pi(R, \bar{s}, \bar{b}) = \pi(R)\pi(\bar{s})\pi(\bar{b}) = s_{tot}\theta(Rs_{tot})\pi(\bar{s})\pi(\bar{b})
\]

\[
s_{tot} = \Sigma_{i,j}s_{ij} : \text{Total number of signal prediction}
\]

\[
\pi(x) = G(x|\hat{x}, \sigma_x) \quad (x = s, b) \quad \hat{x} : \text{expected mean, } \sigma_x : \text{total uncertainty}
\]
CDF Run II Preliminary, $L \leq 8.2 \text{ fb}^{-1}$

95% CL Limit/SM

LEP Excl.

- $\text{WH+ZH+VBF-jlbb 4.0 fb}^{-1} \text{ Obs}$
- $\text{WH+ZH+VBF-jlbb 4.0 fb}^{-1} \text{ Exp}$
- $\text{H-}\gamma\gamma 6.0 \text{ fb}^{-1} \text{ Obs}$
- $\text{H-}\gamma\gamma 6.0 \text{ fb}^{-1} \text{ Exp}$
- $\text{ZH-llll 7.9 fb}^{-1} \text{ Obs}$
- $\text{ZH-llll 7.9 fb}^{-1} \text{ Exp}$
- $\text{ttH MET+jets 5.7 fb}^{-1} \text{ Obs}$
- $\text{ttH MET+jets 5.7 fb}^{-1} \text{ Exp}$
- $\text{WZ+} 6.2 \text{ fb}^{-1} \text{ Obs}$
- $\text{WZ+} 6.2 \text{ fb}^{-1} \text{ Exp}$
- $\text{WH+ZH+METllb 7.8 fb}^{-1} \text{ Obs}$
- $\text{WH+ZH+METllb 7.8 fb}^{-1} \text{ Exp}$
- $\text{WH-}llb 7.5 \text{ fb}^{-1} \text{ Obs}$
- $\text{WH-}llb 7.5 \text{ fb}^{-1} \text{ Exp}$
- $\text{WH-}l\ell llb 7.9 \text{ fb}^{-1} \text{ Obs}$
- $\text{WH-}l\ell llb 7.9 \text{ fb}^{-1} \text{ Exp}$

Combined Obs
Combined Exp

SM=1

WH Search at CDF, Higgs Hunting, Orsay, 2011

July 17, 2011
Exclude at 95% CL: [100.0 - 104.5] & [156.7 - 173.8] GeV/c^2
Expect to exclude at 95% CL: [156.5 - 173.7] GeV/c^2
CDF Combination

- CDF Collaboration, up to 8.2 fb$^{-1}$
- Search for the Standard Model Higgs Boson
- Very many channels
- None sees an excess of signal over backgrounds
- We combine all channels and use a Bayesian statistical approach to compute 95% CL upper limits on the cross section of the Higgs boson
- We expect to exclude at 95% CL Higgs masses in the range : [157.0-172.2] GeV/c$^2$
- We exclude at 95% CL Higgs masses in the ranges [100.0 -104.5] & [156.5-173.7] GeV/c$^2$
- Stay tuned for the Tevatron combination result!
Sensitivity improved continuously more than just by increasing the integrated luminosity; showing 115 and 160 GeV/c²