Experimental Searches for Higgs Bosons at the Tevatron

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on behalf of the CDF and DØ Collaborations

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– Indirect constraints from precision measurements
– The SM Higgs boson
– Higgs bosons in the MSSM and beyond

Full set of Tevatron results available at:
http://www-d0.fnal.gov/Run2Physics/WWW/results.htm
The Tevatron Collider

Proton Antiproton Collider

Centre-of-mass energy: 1.96 TeV

Integrated Luminosity: 6.8 fb\(^{-1}\) so far

Peak luminosity: \(3.5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}\)

Expected to deliver 9-12 fb\(^{-1}\) by 2010/11

Electron Cooling in operation
The Tevatron Collider

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The Tevatron Experiments

Two General-Purpose Detectors:  CDF  DØ

- Electron acceptance  $|\eta| < 2.0$  $|\eta| < 3.0$
- Muon acceptance  $|\eta| < 1.5$  $|\eta| < 2.0$
- Silicon Precision tracking  $|\eta| < 2.0$  $|\eta| < 3.0$
- Hermetic Calorimeter  $|\eta| < 3.6$  $|\eta| < 4.2$

Powerful trigger systems (2.5 MHz→100 Hz)
- Dilepton triggers starting at $p_T > 4$ GeV
- Jets+$E_T$ triggers with $E_T > 25$ GeV
- 6.0 + 5.5 fb⁻¹ recorded by DØ + CDF
- Results presented here based on up to 4.2 fb⁻¹
Pinning down EWSB at the Tevatron

$W/Z \sim \ln \frac{m_H}{m_W}$

Combined top mass measurement from CDF+DØ: $m_t = 173.1 \pm 1.3$ GeV

New DØ $W$ mass measurement (1 fb$^{-1}$): $m_W = 80.401 \pm 0.043$ GeV

- most precise single measurement to date
- not yet included in the world average!
Pinning down EWSB at the Tevatron

\[ H \sim \ln \frac{m_H}{m_W} \]

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New DØ W mass measurement (1 fb\(^{-1}\)): \( m_W = 80.401 \pm 0.043 \text{ GeV} \)

→ Indirect prediction of the Higgs boson mass:
\[ m_H = 90^{+36}_{-27} \text{ GeV and } m_H < 163 \text{ GeV at 95% C.L.} \]
The SM Higgs Boson – Production and Decay

**Production Cross-Sections**

![Graph showing production cross-sections](image_url)

- $\sigma(pp \rightarrow H + X)$ (pb)
- $\sqrt{s} = 2$ TeV

**Branching Ratios**

![Graph showing branching ratios](image_url)

- $BR(H)$
- $M_H$ (GeV)

**Light Higgs boson ($m_H \approx 135$ GeV):**

- Dominant decay mode: $H \rightarrow b\bar{b}$
- Production: in association with $W,Z$
  - $\rightarrow$ leptonic $W,Z$-decays provide best signature
  - $\rightarrow$ b-tagging to suppress background from $W/Z+jets$

**Heavy Higgs boson ($m_H \approx 135$ GeV):**

- Dominant decay mode: $H \rightarrow WW$
- Production: Gluon-Gluon Fusion
  - $\rightarrow$ relatively high cross-section
  - $\rightarrow$ clean 2-lepton+$E_T$ signature via $H \rightarrow WW \rightarrow l\nu l\nu$
Search for low-mass Higgs Boson

Step 1: select W/Z+2jets sample using $W \rightarrow \ell \nu$, $Z \rightarrow \ell \ell$ or $Z \rightarrow \nu \nu$

Note: large efforts to maximize acceptance
- $W/Z$ decays to taus, electrons and muons in cracks...
Search for low-mass Higgs Boson

Step 1: select W/Z+2jets sample using $W \rightarrow \ell \nu$, $Z \rightarrow \ell \ell$ or $Z \rightarrow \nu \nu$

Step 2: calculate dijet mass to reconstruct Higgs resonance
Search for low-mass Higgs Boson

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Step 4: combine full kinematic information in multivariate discriminant
Search for low-mass Higgs Boson

Note: signal-to-background ratios are at most 20-30%
→ need full combination of all channels to reach sensitivity
→ need to control systematics at a level $\ll 20\%$

Main concern: modeling of V+jets backgrounds
- shapes: from MC (alpgen, MCFM, CKKW)
- normalisation: combination of (N)NLO cross-sections and sideband-fitting
Test: Observation of $WW/\!\!/WZ \rightarrow \ell\nu jj$

Similar situation:

- main background is $W+$jets
- signal/background at best 8%

Main problem:

- $W+$jets background modeling uncertainties are large (about 40%)
- systematic uncertainty on background needs to be $\ll 8\%$ to detect a signal

$\rightarrow$ use same techniques as in low-mass Higgs searches, check if signal can be extracted
Test: Observation of WW/WZ\to \ell\nu jj

Result: $\sigma = 20.2 \pm 4.5$ pb (expectation $16.1 \pm 0.9$ pb)

Significance: 4.4 $\sigma$
By now including many low-sensitivity channels initially not considered:

<table>
<thead>
<tr>
<th>Channel</th>
<th>CDF</th>
<th>DØ</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttH with H→bb:</td>
<td>0.3 fb⁻¹</td>
<td>2.1 fb⁻¹</td>
</tr>
<tr>
<td>WH→WWW in SS dileptons:</td>
<td>2.7 fb⁻¹</td>
<td>3.6 fb⁻¹</td>
</tr>
<tr>
<td>Vector Boson Fusion with H→ττ:</td>
<td>2.0 fb⁻¹</td>
<td>1.0 fb⁻¹</td>
</tr>
<tr>
<td>H→γγ:</td>
<td>–</td>
<td>4.2 fb⁻¹</td>
</tr>
</tbody>
</table>

(DØ, 4.2 fb⁻¹ preliminary)

(H→γγ signal expectation: 2.4 events at m_H = 120 GeV)
Search for high-mass Higgs Boson: \( H \rightarrow WW \)

Step 1: two isolated leptons

![Graph showing search for high-mass Higgs Boson: \( H \rightarrow WW \) with two isolated leptons.](image)

- Events at different mass inversions
- Data and background contributions
- M_{inv} [GeV] range from 0 to 200
- Signal region: \( M_{inv} = 165 \)
Search for high-mass Higgs Boson: $H \rightarrow WW$

Step 1: two isolated leptons

Step 2: (significant) missing transverse energy

DØ Preliminary
Run II, 4.2 fb$^{-1}$
$H \rightarrow WW \rightarrow e\mu$
Search for high-mass Higgs Boson: $H \to WW$

Step 1: two isolated leptons

Step 2: (significant) missing transverse energy

Step 3: angular correlations

CDF Run II Preliminary

$M_H = 160 \text{ GeV}/c^2$
Search for high-mass Higgs Boson: $H \rightarrow WW$

Step 1: two isolated leptons

Step 2: (significant) missing transverse energy

Step 3: angular correlations

Step 4: combine full kinematic information in multivariate discriminant

Note: signal-to-background ratio of 50%–100% at high NN
- systematic uncertainties constrained in the control region at low NN
- numerous uncertainties on NN shape, including effects from higher orders:
  - WW pt distribution
  - gg → WW (included by hand)

After background subtraction (H → WW → eνμν only!)
Tevatron Higgs Combination

Tevatron NP & Higgs Working Group: http://tevnphwg.fnal.gov/
- currently combining 75 different channels, many different final states
- full distributions of final variables are analyzed
→ 75 NN/LR/BDT/Mass distributions

> 50 different sources of systematic uncertainties are considered
- taking into account correlations bin-to-bin and channel-to-channel

Systematic uncertainties constrained in “sidebands” (often correlating several channels)
→ very complicated procedure...
- use several techniques (Bayesian, mod. frequentist) and several independent programs to cross-check calculations
→ results agree within 5%
− first (observed) exclusion at 160–170 GeV (effective luminosity: 3.8 fb$^{-1}$)
− only a factor 2.4 away from SM at 115 GeV (effective luminosity: 2.6 fb$^{-1}$)
− still many improvements in the pipeline, expecting to reach sensitivity for entire mass range by end of the run
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Supersymmetry (MSSM)

typically one light SM-like Higgs Boson

new channels: charged Higgs, enhanced bb-Higgs coupling
Search for Charged Higgs Bosons

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Production</th>
<th>Method</th>
<th>Experiment</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H^\pm \to cs$</td>
<td>$t\to H^\pm b$</td>
<td>direct</td>
<td>CDF</td>
<td>2.2 fb⁻¹</td>
</tr>
<tr>
<td>$H^\pm \to \tau \nu, qq$</td>
<td>$t\to H^\pm b$</td>
<td>direct + indirect</td>
<td>DØ</td>
<td>1.0 fb⁻¹</td>
</tr>
<tr>
<td>$H^\pm \to tb$</td>
<td>$qq\to H^\pm$</td>
<td></td>
<td>DØ</td>
<td>0.9 fb⁻¹</td>
</tr>
<tr>
<td>$H^\pm \to \tau \nu$</td>
<td>$t\to H^\pm b$</td>
<td>direct</td>
<td>CDF</td>
<td>0.3 fb⁻¹</td>
</tr>
</tbody>
</table>

CDF Run II Preliminary [2.2fb⁻¹]

DØ Run II Preliminary

- $H^\pm \to c \bar{s}$
  - Expected limit 95% CL
  - Excluded 95% CL

- $H^\pm \to \tau \nu$
  - Expected limit 95% CL
  - Excluded 95% CL

leptophbic

tauonic

$\tan \beta$
Search for Neutral Higgs Bosons with enhanced coupling to $b$

At the end of the chain: looking for a bump in $\tau \tau$ or $bb$ invariant mass:
Search for Neutral Higgs Bosons with enhanced coupling to $b$

**NEW:** Combined MSSM limits based on all DØ channels $\Phi \rightarrow \tau \tau$, $b\Phi \rightarrow bbb$, $b\Phi \rightarrow b\tau \tau$

- same statistical technique as used for the SM Higgs combination

**Plots:**

- **$M_{\Phi} = 130$ GeV**
- **$M_{\Phi} = 220$ GeV**

Largest excess: $2\sigma$ at $M_{\Phi} = 220$ GeV

- Note: not corrected for “look-elsewhere effect”
Search for Neutral Higgs Bosons with enhanced coupling to $b$

NEW: Combined MSSM limits based on all DØ channels $\Phi \rightarrow \tau\tau$, $b\Phi \rightarrow bbb$, $b\Phi \rightarrow b\tau\tau$

- same statistical technique as used for the SM Higgs combination
- additional complication: relative $\sigma \times \text{BR}$, h/H/A masses and widths depend on $m_A$ and $\tan\beta$
Search for N-MSSM Higgs Bosons

- NMSSM Higgs sector: 3 neutral CP-even (h) and 2 CP-odd (a)
- Benchmark scenario not excluded by LEP: \( m_h \sim 100-130 \text{ GeV} \) and \( h \rightarrow aa \)
- New DØ analysis (4.2 fb\(^{-1}\)): \( h \rightarrow aa \rightarrow 4\mu \) or \( 2\mu 2\tau \)

Results:

- \( 2m_\mu < M_a < 2m_\tau \): \( \sigma(p\bar{p} \rightarrow h) \times \text{BR}(h \rightarrow aa \rightarrow 4\mu) \lesssim 10 \text{ fb} \)
- \( M_a > 2m_\tau \): no exclusion, \( 2\sigma \) excess at \( m_a \approx 4 \text{ GeV} \)
Search for N-MSSM Higgs Bosons

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Search for Fermiophobic Higgs Bosons

Analysis similar to SM Higgs search: \( gg \rightarrow H \rightarrow \gamma\gamma \)

Main difference: no gluon fusion for fermiophobic Higgs \( \rightarrow VH \) and VBF only

\[ \rightarrow \text{Higgs bosons are produced with significant } p_T \]

\[ \rightarrow \text{cut on } p_T \text{ of diphoton system} \]

Limits on \( \text{BR}(H \rightarrow \gamma\gamma) \) probing new territory beyond kinematic reach of LEP
Conclusions

Tevatron is running very well: 6 fb$^{-1}$ on tape, good prospects for up to 12 fb$^{-1}$ by 2011

Precision measurements of Top and W mass pinpoint SM Higgs boson mass

SM Higgs search finally reaching sensitivity, first exclusion at 160–170 GeV

SUSY Higgs: limits on tan$\beta$ down to 30 at low $m_A$

For more on this topic:

Search for the Standard Model Higgs Boson at DØ  
Search for Beyond the Standard Model Higgs Bosons at DØ  
Searches for SM and BSM Higgs bosons in CDF  
Measurements of the ttbar Cross Section at DØ and Interpretations
BACKUP
null
Test: Observation of $\text{WW}/\text{WZ} \rightarrow \ell\nu jj$

Step 1: determine k-factor from data, i.e. normalize $Wjj$ cross-section to data

Step 2: fix discrepancies in modeling of angular distributions by reweighting to data (shown to create a negligible bias for cross section measurement)
Step 3: vary alpgen parameters to find range of models consistent with data based on W pt and jet1 pt distributions, excluding mass window around WW/WZ peak.
Step 4: constrain remaining shape uncertainties of dijet mass distribution from sidebands (includes W+jets modeling as well as JES)

Result: $\sigma = 20.2^{+4.5}_{-3.2} \text{ pb}$ (expectation $16.1^{+0.9}_{-1.0} \text{ pb}$)

Significance: $4.4 \sigma$