Search for Beyond the Standard Model Higgs Bosons at the Tevatron

Tim Scanlon

On behalf of the CDF and DØ Collaborations
Outline

- Introduction
  - Tevatron performance
- Neutral Higgs Searches
  - Minimal SUSY SM (MSSM)
  - Next-to-MSSM
  - Fermiophobic Higgs
- Charged Higgs Searches
- Prospects & Conclusions

[Thanks to all my Tevatron colleagues]
Tevatron Performance

Tevatron continues to perform well
- Over 6.5 fb$^{-1}$ delivered to each experiment
- Peak luminosities of $>3.5 \times 10^{32}$

Luminosity projection curves for Run II
- Performance matching design integrated luminosity of $> 7$ fb$^{-1}$ by 2009

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Neutral SUSY Higgs

- **Introduction**

- **Minimal Supersymmetric Standard Model (MSSM)**
  - Introduction
  - Neutral Higgs bosons ($\phi$) searches
    - $\phi \rightarrow \tau\tau$
    - $b\phi \rightarrow bbb$
    - $b\phi \rightarrow b\tau\tau$
  - Next-to-MSSM search

- **Fermiophobic Higgs**

- **Charged Higgs**

- **Prospects & Conclusions**

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Supersymmetric Higgs Sector

- Minimal Supersymmetric Standard Model (MSSM)
  - 2 Higgs doublets
  - 5 Physical Higgs bosons
    - 3 Neutral: (A, h and H) → φ
    - 2 Charged: H\(^±\)
- Need 2 parameters to calculate all Higgs masses and couplings at tree level
  - \(m_A\)
  - \(\tan(\beta) = \) ratio of vacuum expectation values of two Higgs fields
- Coupling of neutral Higgs to b-quarks enhanced by \(\tan(\beta)\)
  - Production enhanced by \(\tan^2(\beta)\)
**MSSM Higgs boson production**

- **Neutral MSSM Higgs decays**
  - $b\bar{b} \sim 90%$
    - Large background
  - $\tau\tau \sim 10%$
    - More distinct signature

- **3 channels best suited to benefit from enhanced $b$-quark coupling**
  - $\phi \rightarrow \tau\tau$
  - $\phi b \rightarrow bbb$
  - $\phi b \rightarrow \tau\tau b$

- **Good $b$-jet and $\tau$ identification vital**

**Similar overall sensitivities → Combine**

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Neutral MSSM Higgs → \( \tau_l \tau_{\text{had}/l} \)

- **Signal:** Three possible search channels
  - \( \tau_\mu \tau_{\text{had}}, \tau_e \tau_{\text{had}}, \tau_e \tau_\mu \) channels
  - Isolated lepton separated from \( \mu/e/\tau_{\text{had}} \) with opposite sign

- **Main bkgs.:** \( Z \rightarrow \tau \tau \) (irreducible), QCD multi-jet, W+jets

- **DØ (\( \mu \)):** 2.2 fb\(^{-1}\) Summer 2008
  - Combined with published 1 fb\(^{-1}\) channels
  - \( \tau_{\text{had}} \) identified using NNs
  - Remove W+jets: Transverse momentum < 40 GeV

- **CDF (\( \mu, e, e+\mu \) channels):** 1.8 fb\(^{-1}\) Summer 2007
  - \( \tau_{\text{had}} \) identified using variable size cone
  - Remove QCD multi-jet: \( |p_T^{\tau}| + |p_T^{l}| + |\text{missing } E_T| > 55 \) GeV
  - Remove W+jets: Cut on relative directions of \( \tau \) decay and missing \( E_T \)
Neutral MSSM Higgs $\rightarrow \tau_l\tau_{\text{had}}$

- $m_{\text{vis}}$ used to derive cross section limits

\[ \tau_e\tau_{\text{had}} + \tau_\mu\tau_{\text{had}} \text{ channels} \]

CDF Run II 1.8 fb$^{-1}$
MSSM $\phi \rightarrow \tau\tau$ Search
Preliminary

\[ m_\phi \text{ (GeV/c}^2\text{)} \]

D$\phi$ Preliminary (1-2.2 fb$^{-1}$)

- $\mu\tau$, $e\tau$, $e\mu$

\[ m_A = 140 \text{ GeV} \]

\[ m_\phi \text{ (GeV/c}^2\text{)} \]

D$\phi$ Preliminary (1-2.2 fb$^{-1}$)
Neutral MSSM Higgs → $\tau_1\tau_{\text{had}}$

- **Set limits**
  - $\sigma \times \text{BR}(\phi \rightarrow \tau \tau) @ 95\%$ confidence level (CL)
  - $90 < m_A < 250$ GeV

- **MSSM scenarios**
  - No-mixing & $m_h^{\text{max}}$ benchmark scenarios
  - $\tan(\beta) > 40 - 60$ excluded for $m_A < 180$ GeV

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**No-mixing, $\mu = +200$ GeV**

**$m_h^{\text{max}}, \mu = +200$ GeV**

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Neutral MSSM Higgs → bb + b[b]

- **Signal**
  - At least 3 b-tagged jets
  - Peak in dijet mass spectrum

- **Background**
  - Heavy flavour QCD
  - Predicted from data/MC

- **D0: 2.6 fb⁻¹ Summer 2008**
  - Neural network b-tagger
  - Separate 3, 4 and 5-jet channels
  - Keep multiple jet pairings
  - Train kinematic likelihood
    - Cut on likelihood
  - Use dijet invariant mass to set limits

- **CDF: 2 fb⁻¹ Winter 2008**
  - Secondary vertex b-tagger
Neutral MSSM Higgs $\rightarrow bb + b[b]$

- Final limits corrected for:
  - Width: Not negligible at high $\tan\beta$
  - MSSM NLO Corrections: Strongest limits for Higgs mass term, $\mu < 0$

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**DØ Preliminary, $L=2.6 ~ fb^{-1}$**

$m_h$ max, $\mu = -200$ GeV

$gb \rightarrow b\phi$

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**Excluded Area**

Expected Limit

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**CDF Run II Preliminary (1.9 ~ fb^{-1})**

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**m_A [GeV/c^2]**

80 100 120 140 160 180 200 220

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**tan\beta**

80 100 120 140 160 180 200

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**m_A (GeV/c^2)**

100 120 140 160 180 200

---

95% C.L. upper limits

expected limit

1\sigma band

2\sigma band

observed limit

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Higgs width included
Neutral MSSM Higgs $\rightarrow \tau\tau_{\text{had}} + b$

- Lower branching ratio/cross section
  - Cleaner final state
  - Similar sensitivity
  - Updated summer 2008

- Signal: $\tau_{\mu}, \tau_{\text{had}} + \text{b-jet}$

- Main bkgs.: $Z+\text{jets}, \text{QCD multi-jets}, tt$

- Selection:
  - Isolated $\mu$ separated from opposite sign $\tau_{\text{had}}$
  - $\tau_{\text{had}}$ identification: NN
  - 1 NN b-tagged jet
  - NN(tt) vs likelihood(QCD) used to set limits
Neutral MSSM Higgs $\rightarrow b\tau_1\tau_{\text{had}}$

- Limits in MSSM parameter space
  - No-mixing & $m_h^{\text{max}}$ benchmark scenarios
Neutral SUSY Higgs

- Introduction

- Minimal Supersymmetric Standard Model (MSSM)
  - Introduction
  - Neutral Higgs bosons ($\phi$) searches
    \[ \phi \rightarrow \tau\tau \]
    \[ b\phi \rightarrow bbb \]
    \[ b\phi \rightarrow b\tau\tau \]
  - Next-to-MSSM search

- Fermiophobic Higgs

- Charged Higgs

- Prospects & Conclusions
• **Next-to-MSSM Higgs Sector**

  - Two additional pseudo-scalar Higgs bosons (s and a)
    - $h \rightarrow aa$ dominates

  - If $m_a < 2m_\tau$
    - Dominant decay $a \rightarrow \mu\mu$
    - Limit on $m_h > 82$ GeV

  - If $2m_\tau < m_a < 2m_b$
    - Dominant decay $a \rightarrow \tau\tau$
    - Limit on $m_h > 86$ GeV

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NMSSM Higgs → aa

- $m_a < 2m_\tau$: $h \rightarrow aa \rightarrow \mu\mu\mu\mu$
  - Two pairs of collinear muons

- **Backgrounds:** QCD, $Z/\gamma^* \rightarrow \mu\mu$

- **Event Selection**
  - Two muons $\Delta R(\mu, \mu) > 1$
  - ‘Companion’ tracks $\Delta R(\mu, \text{track}) < 1$

- **Set 95% limits in 2D mass window**
  - $\sigma \times \text{BR} < 10 \text{ fb}^{-1}$
    - $\sigma_h \sim 1000 \text{ fb}$
    - $m_h = 120 \text{ GeV}$
    - $\text{BR}(h \rightarrow aa) \sim 1$
  - $\text{BR}(a \rightarrow \mu\mu) < 10\%$

DØ Run II Preliminary, 3.7 fb$^{-1}$

- $M_a = 3 \text{ GeV}$
- $M_a = 1 \text{ GeV}$
- $M_a = 0.5 \text{ GeV}$
- $M_a = 0.2143 \text{ GeV}$
- Data
**NMSSM Higgs → aa**

- $2m_b > m_a > 2m_\tau$: $h \rightarrow aa \rightarrow \mu\mu\tau\tau$
  - $\mu$ decay suppressed
  - $\tau$ decay dominates
  - Back-to-back $\mu$ and $\tau$ pairs

- **Backgrounds:** QCD, $Z/\gamma^*+jets \rightarrow \mu\mu+jets$

- **Event Selection**
  - $\mu$ pair $\Delta R(\mu,\mu) < 0.5$, $m_{\mu\mu} < 20$ GeV
  - Missing $E_T > 25$ GeV

- **Set limits @ 95% using dimuon mass**
  - Limit ~4 times larger than Higgs production
Fermiophobic Higgs

- Introduction
- Minimal Supersymmetric Standard Model (MSSM)
- Fermiophobic Higgs
- Charged Higgs
- Prospects & Conclusions
Coupling to fermions highly suppressed

Search for diphoton mass peak
  ~3% resolution

Backgrounds
  Direct production, $\gamma$+jets/dijets, Drell-Yan

Selection: 2 photons
  D0: Central, $p_T^{\gamma\gamma} > 35$ GeV
  CDF: Central or endcap, $p_T^{\gamma\gamma} > 75$ GeV
    - Allowing one endcap electron
    ~doubles acceptance
Fermiophobic Higgs → γγ

- No excess, set limits:
  - 95% CL limit

Excluded $m_{h_f} < 106$ GeV

Excluded $m_{h_f} < 102.5$ GeV
Charged Higgs

• Introduction

• Minimal Supersymmetric Standard Model (MSSM)

• Fermiophobic Higgs

• Charged Higgs

• Prospects & Conclusions
Charged Higgs $\rightarrow$ cs

- Search for $H^\pm$ in top decays

- CDF: Summer 2008 2.2fb$^{-1}$
  - Lepton + jet channel
  - $H^\pm \rightarrow cs$
    - MSSM: $\tan(\beta) < 1$ and $m_{H^\pm} < 130$ GeV

- Di-jet mass used to set limits
  - Assume $BR(H^\pm \rightarrow cs) = 1$
Charged Higgs \( \rightarrow c\bar{s}/\tau\nu \)

- **DØ**: Summer 2008 1fb\(^{-1}\)
- Search top decays in dilepton, lepton+jets, lepton+tau channels
  - Compare predicted/observed yields
- **Two models**:
  - **Tauonic**: \( H^\pm \rightarrow \tau\nu \)
    - MSSM: \( \tan(\beta) > 1 \)
  - **Leptophobic**: \( H^\pm \rightarrow cs \)
    - MSSM: \( \tan(\beta) < 1 \) and \( m_{H^\pm} < 130 \) GeV

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**Graphs**

- **DØ Run II Preliminary**
  - Br(\(H^+ \rightarrow c\bar{s}\)) = 1
  - Data (\(L = 1.0 \text{ fb}^{-1}\))
  - t\(\bar{t}\) Br(\(t \rightarrow H^+b\)) = 0.0
  - t\(\bar{t}\) Br(\(t \rightarrow H^+b\)) = 0.3
  - t\(\bar{t}\) Br(\(t \rightarrow H^+b\)) = 0.6
- **Excluded**
  - Br(\(t \rightarrow H^+b\)) > 0.12-0.2

**Diagrams**

- **Expected limit 95% CL**
- **Observed limit 95% CL**
- **M_{H^\pm} [GeV]**
- **M_{tH} [GeV]**
- **\(\tau\nu\)**
- **leptophobic**
- **tauonic**

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Prospects and Conclusions

- Introduction
- Neutral SUSY Higgs
- Fermiphobic Higgs
- Charged Higgs
- Prospects and Conclusions
Prospects - MSSM Higgs

- Probing very interesting regions
  - > 5.5 fb\(^{-1}\) data available
    - Aiming for rapid inclusion of new data
  - Stable and well developed analyses
    - Algorithmic/analysis improvements

- Short term (this summer)
  - Updated searches:
    - $\phi \rightarrow b\bar{b} + b(b) \& \phi \rightarrow \tau\tau \& b\phi \rightarrow b\tau\tau$
  - New MSSM combination

- Longer term
  - Down to $\tan\beta \sim 20$ for low $m_A$
  - Or discovery
Conclusions

• Tevatron and CDF/ DØ experiments performing very well

• Wide range of beyond SM Higgs searches performed by CDF & DØ with up to 4.2 fb\(^{-1}\) Run II data:
  - No signal observed, but already powerful!

• Updated CDF and DØ analyses soon
  - Rapid accumulation in new data
  - Improvements in analysis techniques
  - MSSM Combination

Very exciting times ahead!
Backup slides
CDF and DØ experiments

- Both detectors extensively upgraded for Run Ila
  - New silicon vertex detector
  - New tracking system
  - Upgraded $\mu$ chambers

- CDF: New plug calorimeter & ToF

- DØ
  - New solenoid & preshowers
  - Run IIb: New inner layer in SMT & L1 trigger

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**τ_{had}-Identification**

- **CDF: Isolation based**
  - CDF: Isolation based
  - 1 or 3 tracks in variable size and isolation cone
  - Validated via W/Z measurements
    - Efficiency ~ 40-50%
    - Jet fake rate < 1%

- **DØ: 3 NN’s for each τ type**
  - Validated via Z’s

- **Diagrams**
  - Type 1: \( \tau \to \pi^\pm \nu \)
  - Type 2: \( \tau \to \pi^\pm \pi^0 \nu \)
  - Type 3: \( \tau \to \pi^\pm \pi^\pm \pi^\pm (\pi^0) \nu \)

- **Efficiency Table**

<table>
<thead>
<tr>
<th>Tau Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Reconstruction</td>
<td></td>
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<tr>
<td>Jets</td>
<td>1.5</td>
<td>10</td>
<td>38</td>
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<tr>
<td>Taus</td>
<td>9.1</td>
<td>50</td>
<td>20</td>
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<td>NN &gt; 0.9</td>
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<tr>
<td>Jets</td>
<td>0.04</td>
<td>0.2</td>
<td>0.8</td>
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<tr>
<td>Taus</td>
<td>5.8</td>
<td>37</td>
<td>13</td>
</tr>
</tbody>
</table>

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b-jet Identification

- MSSM Higgs → bb ~90% of time
  - Improves S/B by > 10

- Use lifetime information
  - Correct for MC/data differences
    - Measured at given operating points

CDF: Secondary vertex reconstruction
- Neutral network increases purity
- Tight = 40% eff, 0.5% mis-tag

DØ: Neural Net tagger
- Secondary vertex & dca based inputs, derived from basic b-tagging tools
- High efficiency, purity
- Tight = 50% eff, 0.5% mis-tag

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Several mature algorithms used:

- 3 main categories:
  - Soft-lepton tagging
  - Impact Parameter based
  - Secondary Vertex reconstruction

Combine in Neural Network:
- vertex mass
- vertex number of tracks
- vertex decay length significance
- chi2/DOF of vertex
- number of vertices
- two methods of combined track impact parameter significances
B-tagging - (DØ) Certification

- Have MC / data differences - particularly at a hadron machine
  - Measure performance on data
    - Tag Rate Function (TRF)
      - Parameterized efficiency & fake-rate as function of $p_T$ and $\eta$
  - Use to correct MC b-tagging rate

- b and c-efficiencies
  - Measured using a b-enriched data sample

- Fake-rate
  - Measured using QCD data

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Data Sample

- Run b-tagging Directly on Data

MC Sample

- Weight MC using b, c and fake-jet TRFs

b-Tagged Data and MC Samples

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Neutral MSSM Higgs $\rightarrow \tau_\ell \tau_{\text{had}}$

- Set limits
  - $\sigma \times \text{Br}(\phi \rightarrow \tau \tau)$ @ 95% confidence level (CL)

MSSM Higgs $\rightarrow \tau \tau$ Search, 95% CL Upper Limit

CDF Run II Preliminary, 1.8 fb$^{-1}$

DØ Preliminary (1-2.2fb$^{-1}$)

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Neutral MSSM Higgs → bb + b[b]

- **Background Prediction**
  - Large multijet background
  - Theoretical cross sections very large errors

- **DØ: Sample Composition**
  - Fit MC to data over several b-tagging points

- **DØ: Background Shape**
  - Use double b-tagged data to predict triple b-tagged background

\[
S_{3\text{Tag}}^{\text{exp}}(D, M_{bb}) = \frac{S_{3\text{Tag}}^{\text{MC}}(D, M_{bb})}{S_{2\text{Tag}}^{\text{MC}}(D, M_{bb})} \times S_{2\text{Tag}}^{\text{data}}(D, M_{bb}).
\]

3 b-tag background  MC correction factor  2 b-tag data

DØ, L=1fb¹

0 b-tags

1 b-tag

2 b-tags

3 b-tags

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• 95% CL limits on branching ratio
  ➢ Extend sensitivity into $m_{hf} > 130$ GeV
    ▪ Not accessible by LEP

**Fermiophobic $h \rightarrow \gamma \gamma$ (3.0 fb$^{-1}$)**

Excluded $m_{hf} < 106$ GeV

Excluded $m_{hf} < 102.5$ GeV
MSSM benchmarks

- Five additional parameters due to radiative correction
  - $M_{\text{SUSY}}$ (parameterizes squark, gaugino masses)
  - $X_t$ (related to the trilinear coupling $A_t \rightarrow$ stop mixing)
  - $M_2$ (gaugino mass term)
  - $\mu$ (Higgs mass parameter)
  - $M_{\text{gluino}}$ (comes in via loops)

- Two common benchmarks
  - Max-mixing - Higgs boson mass $m_h$ close to max possible value for a given $\tan\beta$
  - No-mixing - vanishing mixing in stop sector $\rightarrow$ small mass for $h$

<table>
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<tr>
<th></th>
<th>$m_h$-max</th>
<th>no-mixing</th>
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</thead>
<tbody>
<tr>
<td>$M_{\text{SUSY}}$</td>
<td>1 TeV</td>
<td>2 TeV</td>
</tr>
<tr>
<td>$X_t$</td>
<td>2 TeV</td>
<td>0</td>
</tr>
<tr>
<td>$M_2$</td>
<td>200 GeV</td>
<td>200 GeV</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$\pm$200 GeV</td>
<td>$\pm$200 GeV</td>
</tr>
<tr>
<td>$m_g$</td>
<td>800 GeV</td>
<td>1600 GeV</td>
</tr>
</tbody>
</table>
MSSM evolution

\[ \tan \beta \]

\[ m_A \ (\text{GeV}) \]

- 260 pb\(^{-1}\)
- 1 fb\(^{-1}\)
- 2 fb\(^{-1}\)
- 4 fb\(^{-1}\)
- 8 fb\(^{-1}\)

No mixing
Max. mixing

(DØ 2 fb\(^{-1}\))
(DØ 4 fb\(^{-1}\))
(DØ 8 fb\(^{-1}\))

h/A/H → ττ
95% exclusion sensitivity

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