BSM Higgs Boson Searches at the Tevatron Collider

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for the D0 and CDF Collaborations

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- NMSSM
  - Phenomenology
  - Charged Higgs bosons
  - Light neutral Higgs bosons
Contents

- MSSM
  - Phenomenology
  - Neutral Higgs $\rightarrow bb$
  - Neutral Higgs $\rightarrow \tau^+\tau^-$
  - Charged Higgs bosons
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- SM Extension to Four Fermion Generations

- NMSSM
  - Phenomenology
  - Charged Higgs bosons
  - Light neutral Higgs bosons

Many details omitted
- theory references (computations use FeynHiggs)
- detailed discussions of statistical treatment, systematics
MSSM Higgs Phenomenology: Tree Level

- Higgs bosons in the MSSM: “Type-II” Two-Higgs Doublet Model
  \[ H_u = \begin{pmatrix} H^+_u \\ H^0_u \end{pmatrix}, \quad H_d = \begin{pmatrix} H^0_d \\ H^-_d \end{pmatrix} \]

- 5 Higgs bosons: \( H, h, A \) (neutral), \( H^\pm \) (charged)

- Dependence on 2 new parameters: \( M_A, \tan \beta \equiv \frac{v_u}{v_d} \)

- Masses:
  \[
  m^2_{h,H} = \frac{1}{2} \left( m^2_A + m^2_Z \mp \sqrt{(m^2_A - m^2_Z)^2 + 4 m^2_Z m^2_A \sin^2(2\beta)} \right) \\
  m^2_{H^\pm} = m^2_A + m^2_W
  \]
Higgs bosons in the MSSM: “Type-II” Two-Higgs Doublet Model

\[ H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} \]

5 Higgs bosons: \( H, h, A \) (neutral), \( H^\pm \) (charged)

dependence on 2 new parameters: \( M_A, \tan \beta \equiv \frac{v_u}{v_d} \)

Masses:

\( m_h < m_Z \) (!)

Couplings:

<table>
<thead>
<tr>
<th>SM particle type</th>
<th>( h ) coupling</th>
<th>( H ) coupling</th>
<th>( A ) coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>up-type quarks</td>
<td>( \frac{\cos \alpha}{\sin \beta} )</td>
<td>( \frac{\sin \alpha}{\sin \beta} )</td>
<td>( \cot \beta )</td>
</tr>
<tr>
<td>down-type quarks, ( \ell^\pm )</td>
<td>( -\frac{\sin \alpha}{\cos \beta} )</td>
<td>( \frac{\cos \alpha}{\cos \beta} )</td>
<td>( \tan \beta )</td>
</tr>
<tr>
<td>W, Z bosons</td>
<td>( \sin(\beta - \alpha) )</td>
<td>( \cos(\beta - \alpha) )</td>
<td>0</td>
</tr>
</tbody>
</table>

\( H^\pm tb \) coupling \sim V_{tb} m_t \cot \beta (1 - \gamma_5) + m_b \tan \beta (1 + \gamma_5) \quad \alpha: \text{CP-even Higgs mixing parameter}
### Beyond Tree Level

#### Substantial corrections (e.g. to $m_h$, from top (s)quark loops)

$$
\Delta(m_{h_0}^2) = h^0 - t - h^0 - t - h^0 - t
$$

- mass/coupling dependence on other SUSY parameters
- Embodied in several scenarios (allowing to evade LEP bounds)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$m_h^{max}$</th>
<th>no-mixing</th>
<th>gluophobic</th>
<th>small $\alpha_{eff}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1$, $t_2$ mixing parameter $X_t$</td>
<td>2 TeV</td>
<td>0</td>
<td>-0.75 TeV</td>
<td>-1.1 TeV</td>
</tr>
<tr>
<td>Higgs bilinear coupling $\mu$</td>
<td>$\pm 200$ GeV</td>
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<td>2 TeV</td>
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<tr>
<td>SU(2) gaugino mass $M_2$</td>
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<td>200 GeV</td>
<td>300 GeV</td>
<td>500 GeV</td>
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<tr>
<td>gaugino mass $m_\tilde{g}$</td>
<td>0.8 TeV</td>
<td>1.6 TeV</td>
<td>0.5 TeV</td>
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</tr>
<tr>
<td>sfermion SUSY breaking parm. $M_{SUSY}$</td>
<td>1 TeV</td>
<td>2 TeV</td>
<td>0.35 TeV</td>
<td>0.8 TeV</td>
</tr>
</tbody>
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- Tuned to maximize $m_h$
- Between top squarks
- Suppressed $gg \to h$
- Suppressed $h \to bb, \tau\tau$
**Beyond Tree Level**

- **Substantial corrections** (e.g. to $m_h$, from top (s)quark loops)

\[ \Delta(m_{h^0}^2) = h^0 - h^0 + h^0 \]

- Mass/coupling dependence on other SUSY parameters

- Embodied in several scenarios (allowing to evade LEP bounds)

### Table: Scenarios

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**Main focus of Tevatron analyses**
MSSM Higgs Production at the Tevatron

- LEP analyses focused on ZH associated production
  - exclusion mainly at low $\tan\beta$

![Graph showing m_A (GeV/c^2) vs tanbeta](image)

Theoretically, h excluded by LEP

No Mixing

By LEP

Excluded by LEP

Excluded
MSSM Higgs Production at the Tevatron

- LEP analyses focused on ZH associated production
  - exclusion mainly at low $\tan\beta$

- Most of the Tevatron programme focuses on high $\tan\beta$
  - complementarity: different production mechanisms

![Graphs showing Higgs production cross sections at Tevatron with $\sqrt{s} = 1.96$ TeV for different $m_h$ and $\tan\beta$ values.](Tev4LHC_WG)
**MSSM Higgs Production at the Tevatron**

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![Graphs showing production cross sections at Tevatron](image)
MSSM Higgs Production at the Tevatron

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  - exclusion mainly at low $\tan \beta$

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![Graphs showing mhmax scenario, $\mu=200$ GeV, $\tan \beta=3$ and $\tan \beta=30$]
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![Graphs showing MSSM Higgs boson mass predictions for different scenarios.](image)
MSSM Higgs Production at the Tevatron

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  - exclusion mainly at low \( \tan\beta \)

- Most of the Tevatron programme focuses on high \( \tan\beta \)
  - complementarity: different production mechanisms

General feature:
- masses, production cross sections for A, h/H very similar \( \Rightarrow \) “\( \Phi \)”
- production of “other CP-even boson (H/h) \( \sim \) negligible

Analyses don’t attempt to identify individual Higgs bosons, but look for an overall excess instead
Largest branching fraction (~90%) ... but need extra b jet to be visible

triple b-tagged data, look for excess in invariant mass spectrum of leading b-tagged jets

emphasis on understanding multijet background
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CDF analysis (2.5 fb⁻¹):
create bkgd template shapes from double tagged sample (also in m_{vtx} variable: extra discrimination)
template fit including also signal
in absence of significant excess, use likelihood ratio to derive limits
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\[
Q \equiv \frac{\mathcal{L}(\text{data}|s + \hat{b})}{\mathcal{L}(\text{data}|\hat{b})}
\]
For high $\tan\beta$, the decay widths $\Gamma_\Phi$ become substantial

resonance less easily distinguished $\implies$ loss of sensitivity

$\Delta_b \propto \tan\beta \cdot \mu$
bΦ → bbb (3)

- **D0 analysis (2.6 fb⁻¹):**
  - separation into 3/4/5-jet samples
  - flavour composition estimated using multiple b-tagging criteria
  - **likelihood discriminant** to improve S/B ratio\[ D = \frac{P_{\text{sig}}(\tilde{x})}{P_{\text{sig}}(\tilde{x}) + P_{\text{bkg}}(\tilde{x})} \]
  - using topological information
  - obtain from double-tagged data, use to predict triple-tagged bkgd

![3 jets exclusive](low-mass LH)

![3 jets exclusive](high-mass LH)
bΦ → bbb (3)

DØ analysis (2.6 fb\(^{-1}\)):
- separation into 3/4/5-jet samples
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- obtain from double-tagged data, use to predict triple-tagged bkgd

\[ \mathcal{D} = \frac{P_{\text{sig}}(x)}{P_{\text{sig}}(x) + P_{\text{bkg}}(x)} \]
\[ \Phi \rightarrow \tau^+ \tau^- \]

- Branching fraction only \( \sim 0.1 \), but much cleaner!
  - can use this decay mode with gluon fusion channel
- but need \( \geq 1 \) leptonic decay: \( \tau_\mu \tau_{\text{had}}, \tau_e \tau_{\text{had}}, \tau_e \tau_\mu \)
- \( \tau \) decays \( \Rightarrow \) no sharp mass peak
- substantial backgrounds: \( Z \rightarrow \tau^+ \tau^-, W+\text{jets}, \text{multijets} \)
\( \Phi \rightarrow \tau^+ \tau^- \)

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- substantial backgrounds: \( Z \rightarrow \tau^+ \tau^-, W+\text{jets}, \text{multijets} \)
- CDF published analysis (1.8 fb\(^{-1}\)):
  - using “visible mass”
    \[
    m_{\text{vis}}^2 = (p_{\tau_1} + p_{\tau_2} + \phi_T)^2
    \]
    \[
    \phi_T \equiv (E_T, E_x, E_y, 0)
    \]
  - \( Z \rightarrow \tau^+ \tau^- \) from MC: energy scale
  - instrumental backgrounds:
    from initial looser \( \tau_{\text{had}} \) selection, known fake rate
Branching fraction only $\sim 0.1$, but much cleaner!  
(can use this decay mode with gluon fusion channel)  
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$Z \rightarrow \tau^+\tau^-$ from MC: energy scale  
instrumental backgrounds:  
from initial looser $\tau_{\text{had}}$ selection, known fake rate  
small model dependence!
$\Phi \to \tau^+\tau^-$ (2)

- **D0**: extended published analysis (1 fb$^{-1}$) by 1.2 fb$^{-1}$ ($\tau\mu$ $\tau_{\text{had}}$)
- Analysis similar to CDF ($Z \to \tau^+\tau^-$, instrumental backgrounds)
- optimised (NN) identification of $\tau \to \pi\nu\tau$, $\tau \to \rho\nu\tau$, 3-prong decays
- additional rejection against $W (\to e/\mu \nu) + \text{jets}$ background ($M_T$)

![Graphs showing data and background distributions](image)
$$\Phi \rightarrow \tau^+\tau^- \ (2)$$

- D0: extended published analysis (1 fb^{-1}) by 1.2 fb^{-1} ($\tau_\mu \tau_{\text{had}}$)
- Analysis similar to CDF ($Z \rightarrow \tau^+\tau^-$, instrumental backgrounds)
- Optimised (NN) identification of $\tau \rightarrow \pi\nu\tau$, $\tau \rightarrow \rho\nu\tau$, 3-prong decays
- Additional rejection against $W \ (\rightarrow e/\mu \nu) + \text{jets background} \ (M_T)$

![Graph showing visible mass distribution]
DØ: extended published analysis (1 fb$^{-1}$) by 1.2 fb$^{-1}$ ($\tau\mu$+$\tau_{had}$)

Analysis similar to CDF ($Z \rightarrow \tau^+\tau^-$, instrumental backgrounds)

optimised (NN) identification of $\tau \rightarrow \pi \nu_{\tau}$, $\tau \rightarrow \rho \nu_{\tau}$, 3-prong decays

additional rejection against $W (\rightarrow e/\mu \nu)$ + jets background ($M_T$)

$m_{h_{\text{max}}}^\mu$, $\mu = +200$ GeV

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

Limits generally (slightly) more restrictive than for bbb final state
$b\Phi \rightarrow b\tau^+\tau^-$

- Small overlap with inclusive $\tau^+\tau^-$ search, reduced $Z \rightarrow \tau^+\tau^-$ background at low $m_\Phi$ complementarity

- D0 published analysis ($2.7 \text{ fb}^{-1}$, $\tau_\mu\tau_\text{had}$):
  - dominant backgrounds: $t\bar{t}$, multijet, $Z$+jets
  - estimate multijet background from same-sign events
  - enrich further using two ($t\bar{t}$, multijet) multivariate discriminants

![Graph showing data, $Z$+jets, multijet, $t\bar{t}$, and other backgrounds.](image)
$b\Phi \rightarrow b\tau^+\tau^-$

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- D0 published analysis (2.7 fb$^{-1}$, $\tau_\mu\tau_{\text{had}}$):
  - dominant backgrounds: $tt$, multijet, $Z$+jets
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  - enrich further using two ($tt$, multijet) multivariate discriminants

![Graphs showing results](image)
Small overlap with inclusive $\tau^+\tau^-$ search, reduced $Z \rightarrow \tau^+\tau^-$ background at low $m_\Phi$ complementarity

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- dominant backgrounds: $tt$, multijet, $Z$+jets
- estimate multijet background from same-sign events
- enrich further using two ($tt$, multijet) multivariate discriminants
Combinations

- Several channels with similar sensitivity
  - combining results makes sense!
- DØ: combination of all neutral MSSM Higgs boson results

NB: only 1.2 fb\(^{-1}\) of bTT data used
Combinations

- Several channels with similar sensitivity
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NB: only 1.2 fb$^{-1}$ of bττ data used
Combinations

- Several channels with similar sensitivity
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- D0: combination of all neutral MSSM Higgs boson results
- Tevatron: combination of $\tau^+\tau^-$ results
**Combinations**

- Several channels with similar sensitivity
  - combining results makes sense!
- D0: combination of all neutral MSSM Higgs boson results
- Tevatron: combination of $\tau^+\tau^-$ results

**Graphs:**
- Tevatron Run II Preliminary, $L = 1.8-2.2$ fb$^{-1}$
  - no mixing, $\mu = -200$ GeV
  - no mixing, $\mu = +200$ GeV

The graphs show the exclusion limits and observed limits for the mass of a particle $m_A$ as a function of $\tan\beta$. The limits are distinguished by the color coding:
- Excluded by LEP
- Observed limit
- Expected limit
- Expected limit $\pm 1\sigma$
- Expected limit $\pm 2\sigma$
Charged Higgs Bosons

- Focus on $t \to H^+ b$ decays (heavy $H \to tb$ out of Tevatron reach)
- exploited in multiple ways to search for $H \to cs, \tau \nu$ decays in $tt$ events
- modified distribution of $tt$ events over $l+jets, l+l$, and $l+T_{\text{had}}$ final states
- $l = e, \mu$
- peak in $l+jets$ di-jet invariant mass spectrum ($H \to cs$)

![Graph of branching ratios](image)
Charged Higgs Bosons: \( H \rightarrow \tau \nu \)

- High \( \tan \beta \): dominant decay mode
- D0 analysis (0.9 fb\(^{-1}\)) of \( l^+\tau_{\text{had}} \) mode:
  - separate 3-jet, >3-jet channels
  - significant background from \( W+\text{jets} \) → likelihood discriminant (kinematic/topological variables)
  - Fix \( \sigma(tt) \) to SM value

\( e^+ >3\text{jets} \)

\[ B = B(t \rightarrow H^{+}b) \]

<table>
<thead>
<tr>
<th>Discriminant</th>
<th>Events / 0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>DØ 0.9 fb(^{-1})</td>
</tr>
<tr>
<td></td>
<td>( t\bar{t} (B = 0) )</td>
</tr>
<tr>
<td></td>
<td>Other MC</td>
</tr>
<tr>
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\[ B ≡ B(t \rightarrow H^{+}b) \]

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\( (M_H = 120 \text{ GeV}) \)
Charged Higgs Bosons: $H \rightarrow \tau \nu$

- High $\tan \beta$: dominant decay mode
- D0 analysis (0.9 fb$^{-1}$) of $l^+\tau_{\text{had}}$ mode:
  - separate 3-jet, >3-jet channels
  - significant background from $W+$jets $\Rightarrow$ likelihood discriminant (kinematic/topological variables)
  - Fix $\sigma(tt)$ to SM value

Method does not exploit depletion in other final states...
Charged Higgs Bosons: Combination

- Better alternative: consider \( l+jets, l+l, l+\tau_{\text{had}} \) channels simultaneously
- DØ analysis (1 fb\(^{-1}\)):
  - follow earlier individual analyses, but use \( \varepsilon(M_{H}) \)

\[
\begin{align*}
D\bar{\Omega}, L=1.0 \text{ fb}^{-1} \\
B(H^{+} \rightarrow \tau \nu)=1
\end{align*}
\]

\[
\begin{align*}
\text{Data} \\
t\bar{t} \text{ Br}(t \rightarrow H^{+}b)=0.0 \\
t\bar{t} \text{ Br}(t \rightarrow H^{+}b)=0.3 \\
t\bar{t} \text{ Br}(t \rightarrow H^{+}b)=0.6 \\
\text{background}
\end{align*}
\]

\[
\begin{align*}
D\bar{\Omega}, L=1.0 \text{ fb}^{-1} \\
B(H^{+} \rightarrow c \bar{s})=1
\end{align*}
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\end{align*}
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Published M\(_{H} = 80 \text{ GeV} \)}
Charged Higgs Bosons: Combination

- Better alternative: consider $l+$jets, $l+l$, $l+\tau_{\text{had}}$ channels simultaneously
- DØ analysis ($1 \text{ fb}^{-1}$):
  - follow earlier individual analyses, but use $\varepsilon(M_H)$

Assuming $B(H \to \tau\nu) + B(H \to cs) = 1$
Better alternative: consider $l+\text{jets}, l+l, l+\tau_{\text{had}}$ channels simultaneously

DØ analysis ($1 \text{ fb}^{-1}$):

- follow earlier individual analyses, but use $\varepsilon(M_H)$
- allows for simultaneous fits of $\sigma(tt)$ \implies improvement for small $M_H$!
Charged Higgs Bosons: Combination

- Better alternative: consider $l^+\text{jets}$, $l^+l^+$, $l^+\tau^\text{had}$ channels simultaneously
- D0 analysis ($1 \text{ fb}^{-1}$):
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  - Interpretation in various MSSM scenarios

![Graphs showing excluded 95% CL region and theoretically inaccessible region for $M_{H^+}$ and $\tan\beta$.]
Charged Higgs Bosons: Combination

- Better alternative: consider l+jets, l+l, l+\(\tau\)_{had} channels simultaneously
- D0 analysis (1 fb\(^{-1}\)):
  - follow earlier individual analyses, but use \(\varepsilon(M_H)\)
  - allows for simultaneous fits of \(\sigma(tt)\) \(\rightarrow\) improvement for small \(M_H\)!
- Interpretation in various MSSM scenarios

Leptophobic Higgs: MSSM for low \(\tan\beta\), Multi-Higgs Doublet models
**Charged Higgs Bosons: Combination**

- Better alternative: consider $l+\text{jets}, l+l, l+\tau_{\text{had}}$ channels simultaneously.
- **D0 analysis (1 fb$^{-1}$):**
  - follow earlier individual analyses, but use $\varepsilon(M_{H})$.
  - allows for simultaneous fits of $\sigma(tt)$ \(\Rightarrow\) improvement for small $M_{H}$!
- Interpretation in various MSSM scenarios.

---

**CPX$_{gh}$ scenario:** substantial $H \rightarrow cs$ fraction even for high $22 < \tan{\beta} < 55$

---

[Graph showing exclusion limits for charged Higgs bosons with axes $M_{H^+}$ [GeV] and $\tan{\beta}$ with various exclusion regions.]
Charged Higgs Bosons: $H \rightarrow cs$

- CDF analysis (2.2 fb$^{-1}$) of double-tagged l+jets final states:
  - kinematic fit using $m_t$, (leptonic) $M_W$ constraints
  - binned ML fit to non-b di-jet mass distribution

Overall $tt$ counts not constrained $\Longrightarrow$ reduced sensitivity at $M_H \approx M_W$
Fermiophobic Higgs: $H \rightarrow \gamma\gamma$

- Possible in various (more exotic) SM extensions
- Benchmark model: SM couplings to vector bosons, no couplings to fermions
- D0 analysis (4.2 fb$^{-1}$):
  - $Vh$ and $VBF$ production lumped together (no “$V$” selection)
  - NN $\gamma$ identification
Possible in various (more exotic) SM extensions

Benchmark model: SM couplings to vector bosons, no couplings to fermions

D0 analysis (4.2 fb⁻¹):
- Vh and VBF production lumped together (no “V” selection)
- NN γ identification
- cut on $p_T(\gamma\gamma)$

DØ, 4.2 fb⁻¹ preliminary

- data
- $VH (M_{h^\gamma}=110\text{GeV})$
- $VBF (M_{h^\gamma}=110\text{GeV})$
Fermiophobic Higgs: $H \rightarrow \gamma\gamma$

- Possible in various (more exotic) SM extensions
- Benchmark model: SM couplings to vector bosons, no couplings to fermions
- D0 analysis (4.2 fb$^{-1}$):
  - $Vh$ and $VBF$ production lumped together (no “$V$” selection)
  - NN $\gamma$ identification
  - cut on $p_T(\gamma\gamma)$
  - jj/$\gamma j$ identified using known fake rates
  - fit signal in 20 GeV mass window

![Graph showing data and preliminary results.](image-url)
Fermiophobic Higgs: $H \rightarrow \gamma\gamma$

- Possible in various (more exotic) SM extensions
- Benchmark model: SM couplings to vector bosons, no couplings to fermions
- D0 analysis (4.2 fb$^{-1}$):
  - $Vh$ and $V$BF production lumped together (no “V” selection)
  - NN $\gamma$ identification

![Graph showing $\sigma \times BR(\gamma\gamma)$ vs $M_{h_t}$ (GeV)]

![Graph showing BR($\gamma\gamma$) vs $M_{h_t}$ (GeV)]

**Update from 2.7 fb$^{-1}$**
Fermiophobic Higgs: $H \rightarrow \gamma\gamma$

- Possible in various (more exotic) SM extensions
- Benchmark model: SM couplings to vector bosons, no couplings to fermions
- CDF analysis (3 fb$^{-1}$):
  - $Vh$ and $VBF$ production lumped together (as in D0 analysis)
  - $p_T(\gamma\gamma) > 75$ GeV
  - fit with 10 GeV signal mass window
Fermiophobic Higgs: $H \to \gamma\gamma$

- Possible in various (more exotic) SM extensions
- Benchmark model: SM couplings to vector bosons, no couplings to fermions
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Four Fermion Generations

- Straightforward SM extension
- evade $N_\nu = 3$ constraint by heavy $\nu$
- enhanced $gg \to H$ cross section (factor 7.5 - 9)

Tevatron combined analysis (CDF 4.8 fb$^{-1}$, D0 5.4 fb$^{-1}$) adjusting corresponding SM $H \to W^+W^-$ search:

- correct signal acceptance for different VH, VBF admixtures
Four Fermion Generations

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  - correct signal acceptance for different VH,VBF admixtures
  - $H \rightarrow W^+W^-$ branching fraction affected by decays to heavy fermions 2 scenarios (both: $m_{b'}, m_{t'} \sim 400 - 500$ GeV):
    - $m_\nu = 100$ GeV, $m_{\nu} = 80$ GeV
    - $m_\nu = m_\nu = 1$ TeV
Four Fermion Generations

- Straightforward SM extension
- evade $N_\nu=3$ constraint by heavy $\nu$
- enhanced $gg\rightarrow H$ cross section (factor 7.5 - 9)
- Tevatron combined analysis (CDF 4.8 fb$^{-1}$, D0 5.4 fb$^{-1}$) adjusting corresponding SM $H \rightarrow W^+W^-$ search:
  - correct signal acceptance for different VH, VBF admixtures

Significantly increased exclusion region
- low mass: $131 \text{ GeV} < M_H < 204 \text{ GeV}$
- high mass: $131 \text{ GeV} < M_H < 208 \text{ GeV}$
NMSSM Higgs Phenomenology

- NMSSM: adds one gauge singlet superfield
- preserves $\rho = 1$
- SSB: replaces $\mu$ (MSSM) with dimensionless coupling constant
- Higgs sector:
  - additional CP-odd ($a$) and CP-even ($h$) Higgs boson

- Allows for Higgs loophole at LEP:
  - SM-like $h$ (within LEP kinematic reach), decaying mostly as $h \rightarrow aa$
  - $M_a < 2m_b$: $a \rightarrow \tau\tau, gg, cc$
    - only looked for by OPAL in MSSM context
  - limited to $m_h < 86$ GeV
NMSSM: Charged Higgs Boson

- CDF analysis (2.7 fb-1): search in l+jets sample (regular tt event w/ extra $\tau^+\tau^-$ pair)
- soft $\tau$'s identify through add'l isolated track
- backgrounds:
  - underlying event (universal $p_T$ spectrum, check in l+1/2jet events)
  - $Z/\gamma^*+jets$ (1 lepton missed or from $\tau$ decay)

![Graphs showing pre-tag lepton + 1 jet and pre-tag lepton + 2 jet events](image)
NMSSM: Charged Higgs Boson

- CDF analysis (2.7 fb⁻¹): search in l+jets sample
  (regular tt event w/ extra τ⁺τ⁻ pair)
- soft τ’s identify through add’l isolated track
- backgrounds:
  - underlying event (universal p_T spectrum, check in l+1/2jet events)
  - Z/γ*+jets (1 lepton missed or from τ decay)

Fit as function of both m_a and M_H
- UE normalisation inferred from b-tagged 3-jet data
- signal shown at exclusion level
**NMSSM: Charged Higgs Boson**

- **CDF analysis (2.7 fb⁻¹):** search in l+jets sample (regular tt event w/ extra \( \tau^+\tau^- \) pair)
  - soft \( \tau \)'s identify through add’l isolated track
- **backgrounds:**
  - underlying event (universal \( p_T \) spectrum, check in l+1/2jet events)
  - \( Z/\gamma^*+jets \) (1 lepton missed or from \( \tau \) decay)

Fit as function of both \( m_a \) and \( M_H \)
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NMSSM: Charged Higgs Boson

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![Graph showing 95% CL Exclusion for $t\rightarrow H^+b\rightarrow W^*Ab$](image)

- $BR(A\rightarrow\tau\tau)=1$
- $BR(H^\pm\rightarrow W^\pm A)=1$

![Diagram showing charged Higgs](image)
NMSSM: Neutral Higgs Boson

- D0 analysis (4.2 fb⁻¹): search for $gg \rightarrow h \rightarrow aa$, with $a \rightarrow \mu^+\mu^-/\tau^+\tau^-$ in inclusive dimuon events ($p_T > 10$ GeV)
- $2m_\mu < m_a < 2m_\tau$: muons too collinear to be reconstructed separately association with track ($R < 1$) only (NB: BF uncertain)

![Graph showing $m_2(\mu,\text{track})$ vs $m_1(\mu,\text{track})$.]

- tight ($\mu$+track) isolation criteria
- efficiency for collinear tracks from $K_S$

$$\sigma(p\bar{p} \rightarrow h + X) \cdot B(h \rightarrow aa) \cdot B(a \rightarrow \mu^+\mu^-)^2 < 10 \text{ fb}$$
**NMSSM: Neutral Higgs Boson**

- **D0 analysis (4.2 fb\(^{-1}\)):** search for \(gg \rightarrow h \rightarrow aa\), with \(a \rightarrow \mu^+\mu^-/\tau^+\tau^-\) in inclusive dimuon events \((p_T > 10 \text{ GeV})\)

- **2m_μ < m_a < 2m_τ:** muons too collinear to be reconstructed separately \(\Rightarrow\) association with track \((R < 1)\) only \((\text{NB: BF uncertain})\)

- **m_a > 2m_τ (μ^+μ^-τ^+τ^-):** reconstruct \(a \rightarrow \mu^+\mu^-\) candidates explicitly

- **Use of muons \(\Rightarrow\) low efficiency**

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**Plot:**

- **Data**
- **Background**
- **Signals**

**Legend:**

- **Collimated τ not individually identified: \(E_T / μ / e\)**
- **Background estimated from low-\(E_T\) region**

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NMSSM: Neutral Higgs Boson

- D0 analysis (4.2 fb⁻¹): search for \( gg \rightarrow h \rightarrow aa \), with \( a \rightarrow \mu^+\mu^-/\tau^+\tau^- \) in inclusive dimuon events (\( p_T > 10 \) GeV)
- \( 2m_\mu < m_a < 2m_\tau \): muons too collinear to be reconstructed separately \( \Rightarrow \) association with track (\( R < 1 \)) only (NB: BF uncertain)
- \( m_a > 2m_\tau (\mu^+\mu^-\tau^+\tau^-) \): reconstruct \( a \rightarrow \mu^+\mu^- \) candidates explicitly

![Graphs depicting the observed and expected limits for different masses and production cross-sections.](image-url)
Fermiophobic Higgs boson searches

CDF $W^\pm h \rightarrow W^\pm W^+ W^-$ (2.7 fb$^{-1}$)

D0 hh$W^\pm \rightarrow \gamma\gamma\gamma\gamma W^\pm$ (0.8 fb$^{-1}$)

Doubly charged Higgs boson searches

D0 $H^{++} H^{--} \rightarrow \mu^+ \mu^+ \mu^- \mu^-$ (1.1 fb$^{-1}$)

CDF $H^{++} H^{--} \rightarrow l^+ \tau^+ l^- \tau^-$ (0.3 fb$^{-1}$)
Conclusion & Outlook

- Consolidation in mainstream MSSM analyses
- First MSSM combinations have been performed
- Analyses with significantly larger datasets are underway
- In the near future, the Tevatron will likely continue to play an important role in BSM Higgs physics