Beyond Standard Model
Higgs Searches at the Tevatron

presented by
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Several extensions to SM predict additional Higgs bosons
  - behave similar to SM Higgs, but exhibit different couplings
  - branching ratio of various Higgs decays can be enhanced significantly

I. MSSM Higgs Search
  - 5 physical Higgs bosons
    * $\phi (= h^0, H^0, A^0)$ and $H^\pm$
  - main searches
    * $\phi b \rightarrow b\bar{b}b$
    * $\phi \rightarrow \tau\tau$ and $\phi b \rightarrow \tau\tau b$
    * charged Higgs in top decays

II. next-to-MSSM Higgs (NMSSM)
  - neutral CP-even Higgs boson ($h_{1,2,3}$)
  - neutral CP-odd Higgs boson ($a_{1,2}$)
  - charged Higgs pair ($h^\pm$)

III. Fermiophobic Higgs Search
  - not covered here... see talk by K. Peters, this conference
MSSM Higgs requires 2 doublets
- yields: $\phi (= h^0, H^0, A^0)$ and $H^\pm$

At tree-level, MSSM Higgs fully specified by two free parameters
- $m_A$
- $\tan \beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$
  (ratio of v.e.v. of 2 Higgs doublets)

Radiative corrections introduce dependence on additional SUSY parameters

Inclusive production cross section $\sigma (p\bar{p} \rightarrow h/H/A)$ is enhanced
- enhancement depends on $\tan \beta$

$\phi$ decays, in most parameter space:
- $\phi \rightarrow b\bar{b}$ ($\sim 90\%$)
- $\phi \rightarrow \tau\tau$ ($\sim 10\%$)
  * smaller BR but cleaner signature
  (vs. large QCD background in b mode)
CDF considers $\tau_\mu \tau_{\text{had}}$, $\tau_e \tau_{\text{had}}$, and $\tau_e \tau_\mu$ channels with 1.8 fb$^{-1}$ data, selected by:
- isolated $e$ or $\mu$: opposite-sign (OS) from hadronic $\tau$
- $\tau$'s selected using variable-size cone algorithm
- Suppress $W$+jets background by requirement on relative direction of visible $\tau$ decay products and $E_T$

CDF: $\phi \rightarrow \tau\tau$ Search

- Data agrees with backgrounds for visible mass
  - set $\sigma \times \text{BR}$ limits for $90 \text{ GeV} < m_A < 250 \text{ GeV}$

CDF: PRL 103, 201801 (2009)
DØ: Inclusive $\tau\tau$ Search

- Result using 1.0 fb$^{-1}$ dataset for $\tau_\mu\tau_{\text{had}}$, $\tau_e\tau_{\text{had}}$, and $\tau_\mu\tau_\mu$: PRL 101, 071804 (2008)

- 2.2 fb$^{-1}$ of Run II data considers $\tau_\mu\tau_{\text{had}}$
  - isolated $\mu$ separated from $\tau$: opposite-sign
  - hadronic $\tau$ categorized by decay types
    * discriminated from jets using $\tau$-ID NN
  - $M_\tau < 40$ GeV $\Rightarrow$ reject W+jets

- No excess in data across visible mass spectrum
  - upper limits on $\sigma \times \text{BR}$ as function of $\phi$ mass
    * 2.2 fb$^{-1}$ result:
      $\sim$10 $-$ 20% improvement over 1.0 fb$^{-1}$ search
95% CL exclusion results similar for each experiment
- each reach sensitivity $\tan\beta \sim 40 - 50$ for $m_A < 180$ GeV

Tevatron combination
- with only a fraction of available dataset, probing interesting region of $\tan\beta \sim 30$ [$(m_{top}/m_b)$]
CDF: $\phi b \rightarrow b\bar{b}b$ Search

- $\phi \rightarrow b\bar{b}$ search difficult due to large multijet background
  - consider $\phi$ produced in association with one b-jet
- [updated] 2.2 fb$^{-1}$ data with 3 b-tagged jets
- Model multijet backgrounds using dijet mass of 2 lead jets ($m_{12}$) & flavor separator ($x_{tags}$)
  - search for enhancements in $m_{12}$
95% C.L. Mass-Dependent Cross Section Limits and MSSM Exclusions

- **Limits on $\sigma \times \text{BR}$**
  - Positive deviation at $\sim 140$ GeV for narrow-width case, with $p$-value = 0.9% (trial factors, 5.7% probability to observe such an excess at any masses)
  - General limits applicable to any narrow scalar with $b\bar{b}$ final states produced in association with $b$-jet

- **Translate limits in MSSM benchmark scenarios in ($m_A$, $\tan \beta$) parameter space**
  - Large $\tan \beta$ enhances the $bbH$ coupling as well as increases width of the Higgs
2.6 fb$^{-1}$ search requires 3 b-tagged jets via NN b-tagger

- Improve sensitivity by separating into 3- and 4-jet channels
  - likelihood discriminates b-jet pair via Higgs signal from multijet backgrounds
    * separate low-mass (<130 GeV) and high-mass (>130 GeV) likelihoods
  - analysis relies on shape difference between signal & background
    * use double b-tagged data to predict triple b-tagged background shape

- No excess in dijet invariant mass: set exclusion limits in MSSM benchmark parameter space
  - Higgs mass term, $\mu < 0 \Rightarrow$ enhanced production for 3b mode gives strongest limits
**[updated]** 4.3 fb\(^{-1}\) search considers \(\phi b \rightarrow \tau_\mu \tau_{\text{had}} b\)

- use developed techniques from both \(\phi \rightarrow \tau \tau\) and \(\phi b \rightarrow bbb\) searches
- 2.7 fb\(^{-1}\) dataset result: PRL 104, 151801 (2010)

**Discriminate against different backgrounds via MVA techniques**

- NN based b-tagging algorithm of leading b-tag jet \(\Rightarrow\) suppress \(Z \rightarrow \tau \tau\) (Z+jets)
- construct \(t\bar{t}\) and QCD multijet discriminants per Higgs mass point

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**Take geometrical mean of top, multijet, and b-tag discriminants for final discriminant, \(D_f\)**
95% C.L. mass-dependent limits calculated for $\sigma \times BR$

Translate into MSSM exclusions in $\tan\beta$ vs. $m_A$ space

Search complimentary to $\phi \rightarrow \tau\tau$ channel as it does not suffer from $Z \rightarrow \tau\tau$ background
If $m_{H^\pm} < m_{\text{top}}$: search in top pair sample for decay to $H^\pm$

Consider two search modes based on $H^\pm$ decays

- **Tauonic model:** $H^\pm \rightarrow \tau \nu$ (high $\tan \beta$)
- **Leptophobic model:** $H^\pm \rightarrow c\bar{s}$ (low $\tan \beta$)

Search dilepton, $\ell + \text{jets}$, $\ell + \tau$ top channels

Select high-$p_T$ leptons, $E_T$, and $b$-tag

95% CL limits on $\text{BR}(t \rightarrow H^+ b)$

- DØ 1.0 fb$^{-1}$: PLB 682, 278 (2009)
- CDF 2.2 fb$^{-1}$: PRL 103, 101803 (2009)
next-to-MSSM Higgs decay search, 4.2 fb⁻¹ data
- h→bb branching ratio greatly reduced and dominantly decays to pair of pseudo-scalar Higgs “a”: h→aa
- general LEP search sets limit: M_h > 82 GeV

For masses: 2m_µ < M_a < ~2m_τ (~3.6 GeV)
- dominant decay: aa→µµµµ
  - signature: two pairs of extremely collinear muons due to low M_a
  - σ×BR limits < 5–10 fb (for M_h = 100 GeV)
  - BR(a→µµ) < 7%, assuming BR(h→aa)~1

For masses: 2m_τ < M_a < 2m_b (~9 GeV)
- dominant decay: aa→2µ2τ
  - signature: one pair of collinear muons and large ET from a→ττ decay
  - σ×BR limits: currently are factor of ≈1–4 larger than expected Higgs production

PRL, 103 061801 (2009)
next-to-MSSM Higgs decay search, 2.7 fb⁻¹ data
- search in top quark decays: \( t \rightarrow H^\pm b \rightarrow W^\pm Ab \rightarrow W^\pm \tau \tau b \)
- if charged Higgs \( \sim 100 \) GeV exists \( \Rightarrow BR(t \rightarrow H^\pm b) \sim 10-40\% \)

Search assumes mass of light pseudo-scalar Higgs (A) < 2\( m_b \)
- region not experimentally excluded
- select low-\( p_T \) isolated tracks created by \( \tau \) decay

Data in signal region agrees with expectations, set 95\% CL limits for various \( H^\pm \) and A masses

First such limits in the parameter space of top quark decays
CDF and DØ actively searching for Higgs in models beyond SM
- results with up to 4.3 fb\(^{-1}\) of data reported here

MSSM Higgs
- Tevatron reaching sensitivity of \(\tan\beta \sim 30\) for low \(m_A\)
- forthcoming searches with larger datasets should provide further insight into deviations from expectation at low \(m_A\)
- updated results with new combination expected soon

SM Higgs searches (for e.g., \(H \rightarrow WW\)) could be used to constrain the SM-like Higgs in MSSM
- see P. Draper et al., arXiv:0905.4721v2
- potential to probe significant regions of MSSM parameter space

Tevatron delivered > 9 fb\(^{-1}\) of data and more coming… Stay tuned for exciting results ahead!
Reference Slides
narrow cal clusters matched to low multiplicity tracks

- define [shrinking] signal and isolation cones around seed track’s axis (≡ highest $p_T$ track; > 6 GeV)
- # of tracks inside signal cone defines $\tau$ decay mode
- add $\pi^0$ info to track-cal cluster ⇒ consistent with $\tau$ mass
- $\tau$-id based on “cuts” to key variables (e.g., sum of isolation $E_T$, $p_T$ tracks inside cone)

not associated with hadronic $\tau$ candidate

narrow cal energy clusters matched to tracks, with or without EM subclusters
⇒ separate $\tau$’s into 3 categories, defined by their decay mode

- $\pi\nu$-like [type 1], $\rho\nu$-like [type 2], and 3-prongs [type 3]
- implement Neural Nets (NN) per $\tau$-type to discriminate $\tau$ signal from multijet background

Type 1

$\tau^\pm$ $\rightarrow$ $\pi^\pm$

Type 2

$\tau^\pm$ $\rightarrow$ $\rho^\pm$

Type 3

$\tau^\pm$ $\rightarrow$ $\geq 1$ TRK + wide CAL cluster

signal cone
(shrinking with $\tau$ $E_{\text{cls}}$; $\theta_{\text{sig}} = \text{Min}(10^0, 5 \text{ GeV}/E_{\text{cls}})$)

isolation cone
(annulus: $\theta_{\text{sig}}$ to $\theta_{\text{iso}}=30^0$; $\Sigma E_{\text{iso}} \{\text{trks, } \pi^0\} < [2, 1 \text{ GeV}]$)
After final event selections for $\phi \rightarrow \tau\tau$, irreducible background from $Z \rightarrow \tau\tau$

- smaller contribution from EW and QCD multijet processes

Distinguish Higgs boson by its mass

- presence of neutrinos in final states $\Rightarrow$ not possible to reconstruct $\tau\tau$ mass
- use visible mass: the invariant mass of the sum of the $\tau$ decay plus missing transverse energies
  - exploit fact that signal appears as an enhancement above $Z \rightarrow \tau\tau$

$$M_{VIS} = \sqrt{(P^\tau_1 + P^\tau_2 + P'_T)^2}$$

Use 4-vectors of:

- $P^\tau_1, P^\tau_2$ of visible tau decay products
- $P'_T = (E_T, E_x, E_y, 0)$, where $E_x$ and $E_y$ indicate components of $E_T$

$M_{vis}$ used as input to $\sigma \times BR$ limit calculation
2.6 fb$^{-1}$ search requires

- separate into 3- and 4-jet channels: $p_T^{\text{jet}} > 20$ GeV, $|\eta| < 2.5$
- 3 b-tagged jets with NN based b-tagger, with 2 jets in pair: $p_T^{\text{jet}1,2} > 25$ GeV

6-variable likelihood discriminant [$D$]

- low-mass (3-jets, $m_\phi < 130$ GeV)
- high-mass (3-jets, $m_\phi > 130$ GeV)

Background composition determined from 3-jet sample

- fit MC simulated events to data over b-tagging points: 0-, 1-, 2-, and 3-tag

Background modeling

- irreducible $b\bar{b}b$ background $\Rightarrow$ indistinguishable from any possible signal
- no control regions to normalize to data
  * model background shape using combination of data and simulation
  * predict 3 b-tag bkrgnd shape from 2 b-tag data, scaled by simulated 3/2-tag ratio
### Multivariate Methods: Variables

#### $h_f \rightarrow \gamma\gamma$ Search

**5-variable Neural Network (NN)**

- $\sum_{trks} p_T(trks)$
- $N_{\text{cells}}$ in CAL Layer 1 within $\Delta R < 0.2$
- $N_{\text{cells}}$ in CAL Layer 1 within $0.2 < \Delta R < 0.4$
- number of assoc. CPS clusters with $EM_{\text{CAL}}$
- energy-weighted width of CPS clusters

#### $\phi b \rightarrow \tau_\mu \tau_{\text{had}} b$ Search

**6-variable Likelihood Discriminant** *(for jet pair with 1st and 2nd leading jets)*

- $\Delta\eta$ of 2-jets in the pair
- $\Delta\phi$ of 2-jets in the pair
- angle: $\phi = \cos(\text{lead jet, total }p_T \text{ of jet pair})$
- momentum balance: $\sqrt{|p_{b1}-p_{b2}|} / \sqrt{|p_{b1}+p_{b2}|}$
- combined rapidity of jet pair
- event sphericity

#### $\phi b \rightarrow b\bar{b}b$ Search

**anti-top Discriminant ($D_{\text{top}}$)**

- $D_{\text{final}} = (D_{\text{top}} + D_{Mj} + D_{\text{lead }b-\text{tag}})^{1/2}$

<table>
<thead>
<tr>
<th>$D_{\text{final}}$</th>
<th>$D_{\text{top}}$</th>
<th>$D_{Mj}$</th>
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<tbody>
<tr>
<td>$N_{\text{jets}}$</td>
<td>Muon $p_T$</td>
<td></td>
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<tr>
<td>$H_T = \Sigma_{\text{jets}} p_T[jets]$</td>
<td>Tau $p_T$</td>
<td></td>
</tr>
<tr>
<td>$E_T = p_T^\tau + p_T'^\tau + H_T$</td>
<td>$</td>
<td>\Delta\phi[\mu, \tau]</td>
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<tr>
<td>$</td>
<td>\Delta\phi[\mu, \tau]</td>
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<tr>
<td>$</td>
<td>\Delta\phi[\mu, \text{MET}]</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{M}_T = [p_T'^\tau - p_T^{\tau}] / p_T^{\tau}$</td>
<td>$m_T[\mu, \tau, \text{MET}, \text{jet}]$</td>
<td></td>
</tr>
<tr>
<td>$\muon p_T$</td>
<td>$H_T = \Sigma_{\text{jets}} p_T[jets]$</td>
<td>$m_T[\mu, \tau, \text{MET}, \text{jet}]$</td>
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<tr>
<td>$m_T[\mu, \text{MET}]$</td>
<td>$m_T[\mu, \tau, \text{MET}]$</td>
<td>$m_T[\mu, \tau, \text{MET}, \text{jet}]$</td>
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<td>$m_T[\mu, \tau, \text{MET}, \text{jet}]$</td>
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N-object $m_T$ defined by: $m_T[O_1, ... , O_N] = \sqrt{\sum_{i=1}^{N} \sum_{j=1}^{N} p_T[O_i] \times p_T[O_j] \times (1 - \cos\Delta\phi[O_i; O_j])}$
For neutral Higgs searches: $\sigma \times BR$ limits $\Rightarrow$ interpreted in MSSM

Tree-level: Higgs sector of MSSM described by $m_A$ & $\tan \beta$
- radiative corrections introduce dependence on additional SUSY parameters

Five additional, relevant parameters
- $M_{\text{SUSY}}$ - Common Scalar mass: parameterizes squark, gaugino masses
- $X_t$ - Mixing Parameter: related to the trilinear coupling $a_t \rightarrow$ stop mixing
- $M_2$ - SU(2) gaugino mass term
- $\mu$ - Higgs mass parameter (where $\Delta_b \propto \mu \times \tan \beta$)
- $m_{\tilde{g}}$ - gluino mass: comes in via loops

Two common benchmarks
- $m_h^{\text{max}}$ (max-mixing): Higgs boson mass, $m_h$, close to maximum possible value for a given $\tan \beta$
- no-mixing: vanishing mixing in stop sector $\Rightarrow$ small Higgs boson mass, $m_h$

Constrained Model: Unification of SU(2) and U(1) gaugino masses

<table>
<thead>
<tr>
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<th>$m_h^{\text{max}}$</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>$m_{\tilde{g}}$</td>
<td>800 GeV</td>
<td>1600 GeV</td>
</tr>
</tbody>
</table>
DØ combination across search channels ⇒ $\tan\beta$ vs. $m_A$ exclusions

- $\phi \rightarrow \tau\tau$ (1.0–2.2 fb$^{-1}$), $\phi b \rightarrow \tau\tau b$ (1.2 fb$^{-1}$), and $\phi b \rightarrow \bar{b}b\bar{b}$ (2.6 fb$^{-1}$)
- does not include recent 4.3 fb$^{-1}$ $\phi b \rightarrow \tau\tau b$ search
  * expect new combination soon

- Reach similar sensitivity as Tevatron combination on $\tau\tau$ searches

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### DØ Combination with 3 Search Channels

...see also M. Mulhearn’s talk, this conference
Fermiophobic $h_f \rightarrow \gamma \gamma$ Search

- **DØ 4.2 fb$^{-1}$ result**
- **Distinguish photons with misidentified jet backgrounds using NN**
  - implement energy-weighted width of DØ central preshower clusters
- **Search for excess of events in $\gamma \gamma$ mass spectrum**

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

- **For Fermiophobic couplings, limit set at 95% CL:** $m_{hf} > 102.5$ GeV
- **CDF (3.0 fb$^{-1}$):** $m_{hf} > 106$ GeV
  - each result has reached similar sensitivity as a single LEP experiment
- **Tevatron results:** extend sensitivity for Br($h_f \rightarrow \gamma \gamma$) into $m_{hf} > 125$ GeV region, not accessible by LEP