BSM Higgs and other bump searches at the Tevatron

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on behalf of the CDF and DØ collaborations

CEA Saclay / Irfu / SPP

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Outline

1. MSSM
   - $\phi \rightarrow \tau\tau$ (incl.)
   - $b\phi \rightarrow b\bar{b}b$
   - $b\phi \rightarrow b\tau\tau$
   - Combination

2. Extended Higgs Sector Models
   - Hidden Valley
   - Doubly-Charged Higgs Boson

3. Fermiophobic Higgs search

4. Dijet Mass Spectrum in $W + jj$ Events

Many thanks to the Tevatron

11.9 fb$^{-1}$ of $p\bar{p}$ collisions delivered between April 2002 and September 30th 2011!
The Higgs Sector in the MSSM

- **Two Higgs doublets** (coupling to resp. up- and down-type quarks, with vevs resp. $v_u$ and $v_d$).
  \[
  \tan \beta = \frac{v_u}{v_d}
  \]
  \[
  \tan \beta \approx \frac{m_t}{m_b} \approx 35 \text{ (large tan } \beta \text{) looks natural.}
  \]

- **Five physical Higgs bosons:**
  - Three neutral $A$, $h$, $H$ (collectively denoted $\phi$),
  - Two charged $H^+$, $H^-$.

- **$Hbb$ coupling enhanced by tan $\beta$**
  - Enhanced production cross-section $\sigma(p\bar{p} \rightarrow \phi)$ compared to the SM.
  - $h/A$ or $H/A$ degenerate in mass: $\sigma \times 2$
  - $B(\phi \rightarrow b\bar{b}) \approx 90\%$, $B(\phi \rightarrow \tau^+\tau^-) \approx 10\%$

- **MSSM Higgs sector fully described by $\{m_A, \tan \beta\}$ at tree level.**
  - Radiative corrections make it more model-dependent for $\phi \rightarrow b\bar{b}$.
**τ** identification at the Tevatron

Analyses with **τ** leptons:

- Several channels to combine.
- Missing energy (information) from neutrinos.
- **τ**$_{\text{had}}$: multijet background.

### DØ

**Neural network NN$_{\tau}$**

- Use isolation, shower shape, trk-cal consistency variables
- eff. = 65%, fake rate = 2.5%

### CDF

**Cut-based.**

- Signal / isolation cones, π$^0$ reconstruction
- eff. = 50%, fake rate < 1%

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E. Chapon (CDF and DØ collaborations) | BSM Higgs and other bump searches at the Tevatron
\[ \phi \rightarrow \tau \tau \text{ (incl.)} \] (DØ, CDF)

- **CDF:**
  \[ \tau_\mu \tau_{\text{had}}, \tau_e \tau_{\text{had}}, \tau_e \tau_\mu \] (1.8 fb\(^{-1}\), PRL 103, 201801 (2009))

- **DØ:**
  \[ \tau_e \tau_\mu, \tau_\mu \tau_{\text{had}} \] (5.4 fb\(^{-1}\), PLB 707, 323 (2011)),
  \[ \tau_\mu \tau_{\text{had}} \] (7.3 fb\(^{-1}\), Accepted by PLB, 2012).

- Look for an excess in the visible mass spectrum:
  \[ M_{\text{vis}} = \sqrt{(P_{\tau_{\text{had}}} + P_{\tau_\mu} + E_T)^2} \]
$b\phi \rightarrow b\bar{b}b$ (DØ, CDF)

- $\mathcal{B}(\phi \rightarrow b\bar{b}) \approx 90\%$ at high $\tan \beta$
- Selection: 3-4 high-$p_T$ jets, $\geq 3$ b-jets.
  - CDF $b$-tagging: displaced vertices, vertex mass separation.
  - DØ $b$-tagging: multivariate discriminant.
- Challenging multijet background:
  - Fit the flavor composition from data.
- Use $M_{bb}$ distribution to set limits.
  - CDF: use two leading jets.
  - DØ: jet pair with highest likelihood.

![Graphs and plots](https://example.com/graph.png)
$b\phi \rightarrow b\bar{b}b$: limits

- Both experiments see some excess.
  - DØ: $\approx 2.5\sigma$ at 120 GeV ($\approx 2.0\sigma$ after LEE)
  - CDF: $\approx 2.8\sigma$ at 150 GeV ($\approx 1.9\sigma$ after LEE)
  - A Tevatron $b\phi \rightarrow b\bar{b}b$ combination is in progress.
- Translate limits in MSSM benchmarks scenarios:
  - Big dependence on sign(μ).
  - Large tanβ: enhanced $bbH$ coupling, increased Higgs width.
\[ b\phi \rightarrow b\tau\tau \] (DØ)

Final states: \( \tau_e\tau_{\text{had}} \) (3.7 fb\(^{-1}\), Preliminary), \( \tau_\mu\tau_{\text{had}} \) (7.3 fb\(^{-1}\), PRL 107, 121801 (2011))

- Little sensitive to model parameters (compared to \( b\phi \rightarrow b\bar{b}b \)).
- Less \( Z \rightarrow \tau\tau \) compared to \( \phi \rightarrow \tau\tau \) (incl.)
  - Thanks to the use of \( b \)-tagging.
- Multijet and \( t\bar{t} \) discriminants.
- Limits set on a final discriminant.

E. Chapon (CDF and DØ collaborations)

**DIS 2012**
MSSM combination (DØ)

Combined limits on MSSM neutral Higgs production using:

- $b\phi \rightarrow b\bar{b}b$ (5.2 fb$^{-1}$),
- $b\phi \rightarrow b\tau\mu\tau\text{had}$ (7.3 fb$^{-1}$),
- $\phi \rightarrow \tau\mu\tau\text{had}$ (7.3 fb$^{-1}$, re-analyzed with $b$-jet veto).

Accepted by PLB.

Expected limits:
- $7.3$ fb$^{-1}$\[ττ\]
- $7.3$ fb$^{-1}$\[ττ\]
- $5.2$ fb$^{-1}$\[bbb\]
Hidden Valley (CDF)

- Search for long-lived heavy particles ($c\tau \approx 1\ cm$).
- Decay mode $HV \to b\bar{b}$
- Look at displaced vertex variables: $\psi$, $\zeta$

CDF Run II Preliminary  Lum = 5.8 fb$^{-1}$

Diagram showing displaced vertex variables $\psi$, $\zeta$ and heavy particle decays $HV \to b\bar{b}$.
Doubly-Charged Higgs Boson (DØ)

- Models with two Higgs triplets (branching ratios depend on the model).
- Final state: two hadronic taus and one muon.
- Four channels (nature of the two same-sign leptons, presence of additional leptons).
- First search for $H^{\pm\pm} \rightarrow \tau_{\text{had}}\tau_{\text{had}}X$ at a hadronic collider.

![Graph showing cross section limits and branching ratios](image-url)
Fermiophobic Higgs search (DØ, CDF)

- No coupling to fermions
- $gg \rightarrow H_f$ forbidden: only $VH_f$ and VBF.
- $H_f \rightarrow ff$ forbidden.
  - $H_f \rightarrow \gamma\gamma$ greatly enhanced and dominates the exclusion.
- $H_f \rightarrow \gamma\gamma$ analysis strategy:
  - DØ: Decision tree. Background estimated from MC.
  - CDF: $M_{\gamma\gamma}$ distribution in 3 independent $p_T^{\gamma\gamma}$ bins. Background estimated from sideband fitting (sliding window).
Fermiophobic Higgs (limits)

- \( H_f \rightarrow \gamma\gamma \):
  - limits on \( B(H_f \rightarrow \gamma\gamma) \) converted into limits on \( \sigma \times B(H_f \rightarrow \gamma\gamma) \) using the fermiophobic Higgs benchmark scenario.
  - Combine \( H_f \rightarrow \gamma\gamma \) and \( H_f \rightarrow W^+W^- \) from CDF and DØ (\( \mathcal{L} \leq 8.2 \text{ fb}^{-1} \)).
  - \( m_{H_f} > 119 \text{ GeV/c}^2 \) at 95% C.L.

Tevatron Run II Preliminary \( L \leq 8.2 \text{ fb}^{-1} \)

CDF Run II Preliminary

DØ preliminary, 9.7 fb\(^{-1}\)

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Fermiophobic Higgs search

**Fermiophobic Higgs (limits)**

- **$H_f \rightarrow \gamma\gamma$:**
  - limits on $\mathcal{B}(H_f \rightarrow \gamma\gamma)$ converted into limits on $\sigma \times \mathcal{B}(H_f \rightarrow \gamma\gamma)$ using the fermiophobic Higgs benchmark scenario.
  - Combine $H_f \rightarrow \gamma\gamma$ and $H_f \rightarrow W^+W^-$ from CDF and DØ ($\mathcal{L} \leq 8.2 \text{ fb}^{-1}$)
  - $m_{H_f} > 119 \text{ GeV}/c^2$ at 95% C.L.

![Tevatron Run II Preliminary L ≤ 8.2 fb⁻¹](image)

- New Tevatron combination soon with the full Run II dataset
- E. Chapon (CDF and DØ collaborations)
CDF and DØ disagree... CDF is performing several independent analyses with the full dataset to make a final statement on the subject.

**DØ (4.3 fb⁻¹)**
- No excess seen.
- \( P(M_{jj} = 145 \text{ GeV}, \sigma \times \mathcal{B} = 4 \text{ pb}) = 8 \times 10^{-6} \).

**CDF (7.3 fb⁻¹, 4.3 fb⁻¹ published)**
- Data is 4.1 standard deviations from expectation.
- \( \sigma \times \mathcal{B} = 3.1 \pm 0.8 \text{ pb} \)
The Higgs sector is a good place too for new physics.

- Reported CDF and DØ results with up to the full Run II Tevatron dataset.
- Also $H^\pm$ and NMSSM searches (not reported here).

**MSSM Higgs searches:**

- Look for $\phi \rightarrow b\bar{b}$ and $\phi \rightarrow \tau^+\tau^-$.  
- Different channels with similar sensitivity: combine!

**Extended Higgs Sector and other exotic models.**

- Hidden Valley (long-lived heavy particle).
- Doubly-charged Higgs.
- Fermiophobic Higgs.

**$W + jj$ di-jet mass spectrum.**

- CDF and DØ agree to disagree...
Higgs bosons branching ratios depend only on $m_A$ and $\tan \beta$ at tree level in the MSSM. However radiative corrections make them much more model-dependent, hence the need for additional assumptions (benchmark scenarios):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$m_h^{\text{max}}$ scenario</th>
<th>No-mixing scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_t$</td>
<td>2 TeV</td>
<td>0 TeV</td>
</tr>
<tr>
<td>$\mu$</td>
<td>± 0.2 TeV</td>
<td>± 0.2 TeV</td>
</tr>
<tr>
<td>$M_2$</td>
<td>0.2 TeV</td>
<td>0.2 TeV</td>
</tr>
<tr>
<td>$m_{\tilde{g}}$</td>
<td>0.8 TeV</td>
<td>1.6 TeV</td>
</tr>
<tr>
<td>$M_{\text{SUSY}}$</td>
<td>1 TeV</td>
<td>2 TeV</td>
</tr>
</tbody>
</table>

Note the need to test both signs of the $\mu$ parameter, which has a big impact on radiative corrections (for $\mathcal{B}(\phi \to b\bar{b})$).
• *B* hadrons travel in the detector before they decay.

• **Information used in *b*-tagging:**
  - Secondary vertex,
  - Impact parameters of tracks,

• DØ: Multivariate discriminant.

• CDF: Displaced vertices, $L_{xy}/\sigma$ cut, vertex mass separation.

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![Graph showing b-jet efficiency and non-jet rejection](image)
\( b\phi \rightarrow b\bar{b}b: \) limits (CDF, DØ)

\[
m_A (\text{GeV}/c^2) \quad \tan \beta \\
0 \quad 25 \quad 50 \quad 75 \quad 100 \quad 125 \quad 150 \quad 175 \quad 200
\]

CDF 2.6 fb\(^{-1}\)

- expected limit
- 1σ band
- 2σ band
- observed limit

\( m_h^{\text{max}} \) scenario, \( \mu = -200 \) GeV (\( \Delta_b = -0.21 \))
Higgs width included

\[
95\% \text{ C.L. upper limits}
\]

DØ, 5.2 fb

- DØ exclusion
- LEP exclusion

Observed
Expected

- 1 s.d.\( \pm \)Exp.
- 2 s.d.\( \pm \)Exp.

\( =-200 \) GeV \( \mu \) max, ha) m\( _{h^{-1}} \)DØ, 5.2 fb

- Observed
- Expected
- Exp. ± 1 s.d.
- Exp. ± 2 s.d.
MSSM combination (DØ)

DØ, $L = 5.2-7.3$ fb$^{-1}$

(a) $m_h$ max, $\mu = -200$ GeV

DØ MSSM combination
$\tau_\mu \tau_h + \tau_\mu \tau_h b + bbb$

(b) $m_h$ max, $\mu = +200$ GeV

DØ MSSM combination
$\tau_\mu \tau_h + \tau_\mu \tau_h b + bbb$

(c) no mixing, $\mu = -200$ GeV

DØ MSSM combination
$\tau_\mu \tau_h + \tau_\mu \tau_h b + bbb$

(d) no mixing, $\mu = +200$ GeV

DØ MSSM combination
$\tau_\mu \tau_h + \tau_\mu \tau_h b + bbb$

$\tan\beta$

$M_A$ [GeV]

DØ expected
DØ exclusion
LEP exclusion

CMS obs. 36 pb$^{-1}$ [9]
ATLAS obs. 36 pb$^{-1}$ [10]
NMSSM $h \rightarrow aa$ (DØ)

- PRL 103, 061801 (2009)
- Model with reduced $\mathcal{B}(h \rightarrow b\bar{b})$.
- The dominant decay becomes $h \rightarrow aa$ where $a$ is a light pseudo-scalar Higgs.
- General LEP search limit: $M_h > 82$ GeV.
- For $2m_\mu < M_a < \sim 2m_\tau (\sim 3.6$ GeV): $aa \rightarrow \mu\mu\mu\mu$
  - Two pairs of extremely collinear muons (because of the low $M_a$).
  - $\mathcal{B}(a \rightarrow \mu\mu) < 7\%$ assuming $\mathcal{B}(h \rightarrow aa) \sim 1$.
- For $2m_\tau < M_a < 2m_b (\sim 9$ GeV): $aa \rightarrow \mu\mu\tau\tau$
  - One pair of collinear muons and large $E_T$ from $a \rightarrow \tau\tau$ decay.
Search for a light (mass < 2m_b) NMSSM pseudo-scalar Higgs boson A in top decays, with A → ττ.

- t → H^± b → W^±(*) Ab
- Use the isolated track p_T spectrum to derive limits.

CDF Run II Preliminary, L=2.7fb

- BR(t→H^'b)=0.11
- BR(A→ττ)=1
- BR(H^'→W^'A)=1

Signal, m(H')=90, m(A)=9 GeV/c^2
SM Boson Daughter Tracks
Underlying Event

95% CL Exclusion for t→H^'b→W^'Ab

- BR(A→ττ)=1
- BR(H^'→W^'A)=1

CDF Run II Preliminary, L=2.7fb

- m(A)=4 GeV/c^2
- m(A)=7 GeV/c^2
- m(A)=8 GeV/c^2
- m(A)=9 GeV/c^2

- Expected
- Observed
If $M_{H^\pm} < m_{\text{top}}$, $t \rightarrow H^\pm b$ is allowed.


DØ: PLB 682, 278 (2009) (1.0 fb$^{-1}$).

Two scenarios:
- $H^\pm \rightarrow \tau \nu$ (high tan $\beta$),
- $H^\pm \rightarrow c\bar{s}$ (low tan $\beta$).

Look at $l^+ + \text{jets (CDF+DØ)}$, dilepton and $l\tau_{\text{had}}$ events (DØ).
PRL 103, 071801 (2009) (3.6 fb⁻¹)
$W + jj$: quark vs. gluon jets (CDF)

Parton composition in $Wjj$, CTEQ6L, $p_T > M_T' + p_T^{T'}$

<table>
<thead>
<tr>
<th>gg</th>
<th>qq</th>
<th>qg</th>
<th>gg</th>
</tr>
</thead>
</table>

No cut (less $qq$)

$E_T^{j1}/E_T^{j2} > 0.6$

$E_T^{j1}/E_T^{j2} > 0.8$ (more $qq$)

CDF

| gg | gg | gg | gg |

4.8σ

3.6σ

3.2σ
$W + jj$: other tests (CDF)

JES shifted by $+7\%$ (twice the systematic uncertainty)

$W + \text{jets modeled by SHERPA (instead of ALPGEN)}$

For more information