Searching for neutral Higgs bosons in non-standard channels

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Motivation

- A SM-Higgs like resonance has been observed at the LHC
- The Higgs sector may also have extra scalars and pseudo-scalars.
- The $\tau\tau$-channel is the standard mode of searching for such particles.
- Examples of models with suppressed $A/H \to \tau\tau$ rates:
  - Enhanced $b\bar{b}$ couplings in 2HDM and MSSM.  
  - Enhance $Z\bar{A}$ couplings in NMSSM like models. 
    \textit{JHEP 1302 (2013) 152 w/ S. Chang}
Searching Non-Standard Higgses with enhanced $b\bar{b}$ rates
Higgs Sector in 2HDMs

- The **Neutral** components acquire **vevs** and their ratio is \( \tan \beta = \frac{v_u}{v_d} \).
- Neglecting **CP** violation in the Higgs sector, electroweak breaking leaves:
  - 1 CP odd Higgs \( A \)
  - 1 charged Higgs \( H^\pm \), and
  - 2 CP even Higgs bosons \( h, H \)
- **One CP-even** (SM-like) Higgs has SM strength couplings to **gauge bosons**.
- The other **CP-even** (Non-Standard) Higgs has **suppressed** couplings to **gauge bosons**.
Couplings to $b$-quarks and $\tau$-leptons in 2HDMs

- **General 2HDM** Higgs fermions couplings are

$$\mathcal{L}_{\text{Yuk}} = y_u H_u \bar{Q} U + y_d H_d \bar{Q} D + \tilde{y}_u H_d^\dagger \bar{Q} U + \tilde{y}_d H_u^\dagger \bar{Q} D + y_\ell H_d \bar{L} E + \tilde{y}_\ell H_u^\dagger \bar{L} E + h.c.$$  

- **d-type fermion coupling**s to **Non-standard Higgses** are:

$$g_{H/Af} \approx \frac{\bar{m}_f}{v} \tan \beta_{\text{eff}}$$

where for $f = b, \tau$

$$\tan \beta_{\text{eff}} = \frac{\tan \beta}{1 + \epsilon_f \tan \beta \left(1 - \frac{\epsilon_f}{\tan \beta}\right)}$$

$$\epsilon_f = \frac{\tilde{y}_f}{y_f}$$

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Fermion couplings in the MSSM

- Including 1-loop effects, both quarks couple to both the Higgs bosons so that:

\[-\mathcal{L}_{\text{eff}} = \overline{d}_R \hat{Y}_d [\Phi^0_d + \Phi^*_u (\hat{c}_0 + \hat{c}_Y \hat{Y}^\dagger_u \hat{Y}_u)] d_L^0 + h.c.\]

and have the structure:

\[
\epsilon_0' \approx \frac{2\alpha_s}{3\pi} M_3 \mu C_0 (m^2_{\tilde{q}_1}, m^2_{\tilde{q}_2}, M^2_3)
\]

\[
\epsilon_Y \approx \frac{1}{16\pi^2} A_{t\mu} C_0 (m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2}, \mu^2)
\]

\[
\epsilon_\tau \approx \frac{3\alpha_2}{8\pi} \mu M_2 C_0 (M^2_{\tilde{\tau}_1}, M^2_{\tilde{\tau}_2}, M^1_1)
\]

Kolda, Babu, Buras, Roszkowski...
Non-standard Higgs boson production and decay

Gunion et.al. ’94, Balazs et.al, Diaz-Cruz et.al., & Huang et.al. ’98, Campbell et.al. ’03, Dawson et.al. ’03

- General $b$ and $\tau$ couplings are

$$g_{Abb} \sim \frac{m_b \tan \beta_{\text{eff}}^b}{v}, \quad g_{A\tau\tau} \sim \frac{m_\tau \tan \beta_{\text{eff}}^\tau}{v}$$
contd...

- Enhanced production and decay modes:

\[
\frac{\sigma(b\bar{b} \to A)}{\sigma(b\bar{b}h)_{\text{SM}}} \mathcal{B}\mathcal{R}(A \to b\bar{b}) \propto \frac{9(\tan\beta_{\text{eff}})^4}{(\tan\beta_{\text{eff}})^2 + 9(\tan\beta_{\text{eff}})^2},
\]

\[
\frac{\sigma(gg, b\bar{b} \to A)}{\sigma(gg, b\bar{b} \to h)_{\text{SM}}} \mathcal{B}\mathcal{R}(A \to \tau\tau) \propto \frac{(\tan\beta_{\text{eff}})^2(\tan\beta_{\text{eff}})^2}{(\tan\beta_{\text{eff}})^2 + 9(\tan\beta_{\text{eff}})^2},
\]

- In the MSSM the $b\bar{b}$ channel has greater model dependence than $\tau\tau$. Carena et.al. ’05

[Graphs showing $\tan\beta$ vs. $M_A$ for different values of $\mu$.]
Non-Standard Higgs into 3b: Production and Decay

- $\tan \beta_{\text{eff}}^\tau$ can be small compared to $\tan \beta_{\text{eff}}^b \Rightarrow$ weaker reach in the $\tau\tau$ channel.
- The $H/A \rightarrow b\bar{b}$ can be enhanced enough to make it competitive with the clean $\tau\tau$ channel.
- In addition to the 4b-final state we also have:

\[ \begin{align*}
&g \\
&b \\
&b \\
&H/A
\end{align*} \]

- 3b channel can be important at 14 TeV LHC for mSUGRA

Cao et.al. ’09, Baer et. al. ’11
Signal and Background Distributions for $\tan \beta = 30$

- Total SM Background
- Signal ($M_{H,A} = 200$ GeV) $\times 10$
- Signal ($M_{H,A} = 300$ GeV) $\times 10$
Reach in the general 2HDM Model
The 3b vs $\tau\tau$ in the MSSM
CMS Analysis

CMS preliminary 2.7-4.8 fb⁻¹ √s = 7 TeV

MSSM mₜₜ-max
μ = +200 GeV

MSSM mₜₜ-max
μ = -200 GeV

arXiv: 1302.2892
Conclusions

• The $A \rightarrow \tau\tau$ LHC search puts weak limits on regions of large $\tan \beta_{\text{eff}}^b$ and small $\tan \beta_{\text{eff}}^\tau$ in 2HDMs.
• The $A/H \rightarrow b\bar{b}$ is a complementary channel that probes parametric scenarios of large $\tan \beta_{\text{eff}}^b$.
• The reach of the $A/H \rightarrow b\bar{b}$ channel is limited by low $S/B$ for low to moderate $\tan \beta_{\text{eff}}^b$, but can be powerful at large $\tan \beta_{\text{eff}}^b$. 
Search for Non-Standard Higgs in the $H \rightarrow ZA$ channel
Motivation: excess in the $2\ell^+ 0, 1$ and $2\tau_h$'s

- CMS 2011: $2.1 \text{ fb}^{-1}$ @ 7 TeV CMS-PAS-SUS-11-013

<table>
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<tr>
<th>Selection</th>
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- CMS 2012: $4.8 \text{ fb}^{-1}$ @ 7 TeV arXiv:1204.5341

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<td>$4\ell E_T^\text{miss} &gt;50, H_T &gt;200$, no Z</td>
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<td>0.018 ± 0.005</td>
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<td>33</td>
<td>37 ± 15</td>
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Theoretical Implications of Signal

- The **multi-lepton channel** is sensitive to **SM Higgs** decay modes and with $5 \text{ fb}^{-1}$ of data, the region $120 \leq m_h \leq 150 \text{ GeV}$ can be probed at 95% C.L.
  
  **E. Contreras-Compana, et.al. ’12**

- The **CMS 2012 multi-lepton data** puts limits on $\mathcal{B}\mathcal{R}(t \rightarrow ch) < 2.7\%$
  
  **N. Craig et.al. ’12**

- It also leads to constraints on **2HDM’s** when multiple-channels from $h, H, A$ and $H^\pm$ decay modes.
  
  **N. Craig et.al. ’13**
Example: The NMSSM

- The superpotential has the form

\[ W = W_{\text{Yuk}} + \lambda \hat{H}_u \hat{H}_d \hat{S} + \frac{\kappa}{3} \hat{S}^3 \]

with soft terms

\[ V_{\text{soft}} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + \sqrt{2} \left( m_\lambda S H_u H_d - \frac{m_\kappa}{3} S^3 \right) \]

with \( m_\kappa \equiv -\kappa A_\kappa / \sqrt{2} \) and \( m_\lambda \equiv \lambda A_\lambda / \sqrt{2} \)

- In the basis where scalar basis \((h^0_V, H^0_V, h^0_S)\) and the pseudo-scalar basis \((A^0_V, A^0_S)\)

\[ \mathcal{L}_{\text{Kin Higgs}}^\text{Kin} \subset -\frac{g_2}{2c_{\theta_W}} Z^\mu \left( c_{\theta_A} A_1^0 - s_{\theta_A} A_2^0 \right) \partial_\mu \left( s_{2\beta} h^0_V + c_{2\beta} H^0_V \right) \]

where the \( h^0_V \) is direction that acquires a VEV.

- \( H \rightarrow Z^{\tau^+ \tau^-} \) Has been studied in context of explaining LEP anomalies.

Dermisek ’08, Dermisek and Gunion ’09
Higgs mass of Benchmark points

<table>
<thead>
<tr>
<th>Model</th>
<th>$\lambda$</th>
<th>$\kappa$</th>
<th>$t_\beta$</th>
<th>$A_\lambda$ (GeV)</th>
<th>$A_\kappa$ (GeV)</th>
<th>$A_t$ (TeV)</th>
<th>$\mu_{\text{eff}}$ (GeV)</th>
<th>$M_{q}$ (TeV)</th>
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<tr>
<td>BM1</td>
<td>0.71</td>
<td>1.10</td>
<td>1.5</td>
<td>-11.0</td>
<td>-8.0</td>
<td>0.0</td>
<td>160</td>
<td>0.5</td>
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<td>BM2</td>
<td>0.71</td>
<td>1.10</td>
<td>1.5</td>
<td>-9.1</td>
<td>-7.0</td>
<td>0.0</td>
<td>166</td>
<td>0.5</td>
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<tr>
<td>BM3</td>
<td>0.67</td>
<td>0.78</td>
<td>1.5</td>
<td>-4.2</td>
<td>-40.6</td>
<td>0.0</td>
<td>170</td>
<td>0.5</td>
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<table>
<thead>
<tr>
<th>Model</th>
<th>$m_{H_1^0}$ (GeV)</th>
<th>$m_{H_2^0}$ (GeV)</th>
<th>$m_{A_1^0}$ (GeV)</th>
<th>$m_{H^\pm}$ (GeV)</th>
<th>$g_{t\bar{t}H_1^0}^{\text{red.}}$</th>
<th>$g_{t\bar{t}H_2^0}^{\text{red.}}$</th>
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<td>BM1</td>
<td>125.2</td>
<td>270</td>
<td>8.9</td>
<td>266</td>
<td>0.982</td>
<td>-0.691</td>
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<tr>
<td>BM2</td>
<td>125.1</td>
<td>283</td>
<td>19.7</td>
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<td>BM3</td>
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<td>252</td>
<td>117</td>
<td>248</td>
<td>0.992</td>
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Higgs couplings of Benchmark points

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<tr>
<th>$\mathcal{BR}$ of $H_1^0$</th>
<th>$b\bar{b}$</th>
<th>$\gamma\gamma$</th>
<th>$WW^*$</th>
<th>$ZZ^*$</th>
<th>$A_1^0A_1^0$</th>
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<tr>
<td>BM1</td>
<td>0.63</td>
<td>$2.6 \times 10^{-3}$</td>
<td>0.19</td>
<td>$2.1 \times 10^{-2}$</td>
<td>$2.9 \times 10^{-3}$</td>
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<tr>
<td>BM2</td>
<td>0.61</td>
<td>$2.5 \times 10^{-3}$</td>
<td>0.18</td>
<td>$2.0 \times 10^{-2}$</td>
<td>$4.3 \times 10^{-2}$</td>
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<tr>
<td>BM3</td>
<td>0.64</td>
<td>$2.7 \times 10^{-3}$</td>
<td>0.18</td>
<td>$2.0 \times 10^{-2}$</td>
<td>0.0</td>
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</table>

$\mathcal{BR} : \gamma\gamma_{\text{SM}} = 2.28 \times 10^{-3}; \ WW^*_{\text{SM}} = 2.15 \times 10^{-1}; \ ZZ^*_{\text{SM}} = 2.64 \times 10^{-2}$

<table>
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<tr>
<th>$\mathcal{BR}$ of $H_2^0$</th>
<th>$b\bar{b}$</th>
<th>$H_1^0H_1^0$</th>
<th>$ZA_1^0$</th>
<th>$A_1^0A_1^0$</th>
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<tbody>
<tr>
<td>BM1</td>
<td>$4.5 \times 10^{-3}$</td>
<td>$5.6 \times 10^{-4}$</td>
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<td>0.17</td>
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<tr>
<td>BM2</td>
<td>$4.3 \times 10^{-3}$</td>
<td>$4.9 \times 10^{-4}$</td>
<td>0.70</td>
<td>0.16</td>
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<td>BM3</td>
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<td>$1.7 \times 10^{-6}$</td>
<td>0.78</td>
<td>0.19</td>
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<table>
<thead>
<tr>
<th>$\mathcal{BR}$ of $A_1^0$</th>
<th>$\tau\tau$</th>
<th>$b\bar{b}$</th>
<th>$gg$</th>
<th>Signal Rate ($\mu$)</th>
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<td>BM1</td>
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<td>BM2</td>
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<td>$1.1 \times 10^{-2}$</td>
<td>$5.7 \times 10^{-3}$</td>
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<td>BM3</td>
<td>$9.1 \times 10^{-2}$</td>
<td>0.87</td>
<td>$2.9 \times 10^{-2}$</td>
<td>0.01</td>
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\( \tau_h \) reconstruction

- \( \tau_h \) reconstruction: 1-pronged track with \( p_T \geq 8.0 \text{ GeV} \).
- \( \tau_h \) isolation: \( \frac{E_{\text{ann}}}{E_{\text{cone}}} \leq 0.15 \) where,
  \( E_{\text{ann}} = \text{energy in } 0.1 < \Delta R \leq 0.3 \)
  \( E_{\text{cone}} = \text{energy in } \Delta R \leq 0.1 \).

![Graph showing \( \tau_h \) Reconstruction Efficiency in \( Z \rightarrow \tau\tau \) events]
$\mathcal{Z}\tau\tau$ efficiency in

\[
\epsilon = \frac{\text{Number of events to pass cuts}}{\text{Number of events generated}}
\]
Toy-Model for $\tau_h$ reconstruction

$m_H = 200$ GeV and $m_A = 10$ GeV

$$\theta_{CM} = \text{Angle of } \pi^+ \text{ in rest frame of } A \text{ when } \tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$$

$p_T$ is measured in the $H$ rest frame

$\Delta R =$ the angle between the two charged tracks.
Limits of signal due to CMS data

- Assuming a Poisson distribution for the number of events.
- Assuming the background errors are gaussian

7 TeV
$1-\tau_h$ constraint is the strongest due to large $\epsilon_1\tau_h$ and

$N_{\text{obs}}^{\text{CMS}} \sim N_{\text{bkg}}$
H and A Mass reconstruction in the $2\tau_h$ channel

- **Transverse Mass:**

  \[
  m_A^T = \sqrt{p_V^2 + 2(E_V E_+ - p_V^T \cdot p_+^T)}
  \]

  \[
  m_H^T = \sqrt{(p_V + p_Z)^2 + 2((E_V + E_Z)E_+ - (p_V^T + p_Z^T) \cdot p_+^T)}
  \]

  where $m_i^T \leq m_i$

  **Barr et. al., 2009**

- **Collinear Mass:** Solve kinematics under assumption that neutrinos are collinear with the visible momenta

  \[
  \lambda_1 p_{V_1}^T + \lambda_2 p_{V_2}^T = p_+^T.
  \]

  where by assumption $\lambda_i$’s are positive.

  **Ellis et. al., 1987**
H and A Trial Mass Reconstruction in the $2\tau_h$ channel

- The 8 kinematic constraint equations are:

\begin{align*}
    p_{\nu_1}^2 &= 0 = p_{\nu_2}^2 \\
    (p_{\nu_1} + p_{\nu_1})^2 &= m_\tau^2 = (p_{\nu_2} + p_{\nu_2})^2 \\
    m_A^2 &= (p_{\nu_1} + p_{\nu_1} + p_{\nu_2} + p_{\nu_2})^2 \\
    m_H^2 &= (p_Z + p_{\nu_1} + p_{\nu_1} + p_{\nu_2} + p_{\nu_2})^2 \\
    p_{\nu_1}^x + p_{\nu_2}^x &= p_+^x \\
    p_{\nu_1}^y + p_{\nu_2}^y &= p_+^y
\end{align*}

- However 10 unknowns $p_{\nu_i}$, $m_H$ and $m_A$.
- Solve for the mean values of $m_H$ and $m_A$ where solutions exist.
Comparison of Mass reconstructions

Mass Variables: \((m_H, m_A) = (200, 10)\) GeV

Mass Variables: \((m_H, m_A) = (300, 100)\) GeV

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Arjun Menon  University of Oregon
Latest CMS analysis

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<thead>
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<th>Selection</th>
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<td>( \text{OSSF0} )</td>
<td>( \text{NA} ) (100,100)</td>
<td>0</td>
<td>0.007 ± 0.01</td>
<td>0</td>
<td>0.01 ± 0.02</td>
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<tr>
<td>( \text{OSSF0} )</td>
<td>( \text{NA} ) (50,100)</td>
<td>0</td>
<td>0 ± 0.01</td>
<td>0</td>
<td>0.007 ± 0.01</td>
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<td>1e-05 ± 0.009</td>
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<td>0.01 ± 0.01</td>
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<td>0.13 ± 0.07</td>
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<td>( \text{OSSF2} ) off-Z (100,∞)</td>
<td>0</td>
<td>0.004 ± 0.01</td>
<td>0</td>
<td>0 ± 0</td>
<td>0</td>
</tr>
<tr>
<td>( \text{OSSF2} ) on-Z (100,∞)</td>
<td>0</td>
<td>0.05 ± 0.05</td>
<td>0</td>
<td>0 ± 0</td>
<td>0</td>
</tr>
<tr>
<td>( \text{OSSF2} ) off-Z (50,100)</td>
<td>0</td>
<td>0.01 ± 0.01</td>
<td>0</td>
<td>0 ± 0</td>
<td>0</td>
</tr>
<tr>
<td>( \text{OSSF2} ) on-Z (50,100)</td>
<td>0</td>
<td>0.39 ± 0.1</td>
<td>0</td>
<td>0 ± 0</td>
<td>0</td>
</tr>
<tr>
<td>( \text{OSSF2} ) off-Z (0,50)</td>
<td>0</td>
<td>0.11 ± 0.03</td>
<td>0</td>
<td>0 ± 0</td>
<td>0</td>
</tr>
<tr>
<td>( \text{OSSF2} ) on-Z (0,50)</td>
<td>2</td>
<td>3.3 ± 0.7</td>
<td>0</td>
<td>0 ± 0</td>
<td>1</td>
</tr>
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</table>

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But visible \( p_T^{\tau} \geq 20 \text{ GeV} \) ⇒ reduced efficiencies.
Conclusion

• The possibility of enhanced $H \rightarrow ZA \rightarrow Z\tau^+\tau^-$ decay exists.

• The NMSSM example scenario needs low $\tan \beta$ and large pseudo-scalar mixing.

• The efficiencies for detecting such a scenario are the largest in the $1\tau_h$ and $2\tau_h$ channel.

• The shape of the efficiency curves is due to an interplay between the isolation and $\min(\rho_T)$ cuts.

• For low $m_A$ a boosted $\tau$ strategy similar to Englert et. al., ’11 may be needed.
• $1-\tau_h$ is the most constraining of the channels.
• The projected reach with 30 fb$^{-1}$ CMS data could probe a large region interesting parameter space.
• For such decays the trial mass reconstruction method is more efficient than the transverse and collinear approaches.
• The phenomenology of non-Standard Higgs bosons can be quite rich and appear in many channels other than $\tau\tau$. 