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 $A/H \rightarrow \tau\tau$ rates:
  - Enhanced $b\bar{b}$ couplings in 2HDM and MSSM.
  - Enhance $Z\alpha$ couplings in NMSSM like models.
    - 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 \( \tan \beta = v_u / v_d \).

- Neglecting **CP** violation in the Higgs sector, electroweak breaking leaves:
  
  1. **1 CP odd Higgs** \( A \)
  2. **1 charged Higgs** \( H^\pm \), and
  3. **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 couplings to Non-standard Higgses are:

\[
g_{H/Af} \sim \frac{\tilde{m}_f}{v} \tan \beta_{\text{eff}}
\]

where for $f = b, \tau$

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

\[
\epsilon_f = \frac{\tilde{y}_f}{y_f}
\]
Fermion couplings in the MSSM

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

\[-L_{\text{eff}} = \bar{d}_R \hat{Y}_d [\Phi_d^{0*} + \Phi_u^{*0} \left( \hat{c}_0 + \hat{c}_Y \hat{Y}_u^\dagger \hat{Y}_u \right)] d_L^0 + h.c.\]

and have the structure:

\[
\epsilon_0' \approx \frac{2\alpha_s}{3\pi} M_3 \mu C_0 \left( m_{\tilde{d}_1^l}, m_{\tilde{d}_2^l}, M_3^2 \right)
\]

\[
\epsilon_Y \approx \frac{1}{16\pi^2} A_t \mu C_0 \left( m_{\tilde{t}_1^l}, m_{\tilde{t}_2^l}, \mu^2 \right)
\]

\[
\epsilon_\tau \approx \frac{3\alpha_2}{8\pi} \mu M_2 \mu C_0 \left( M_{\tilde{\tau}_1^l}, M_{\tilde{\tau}_2^l}, M_1^2 \right)
\]

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

General $b$ and $\tau$ couplings are

$g_{Abb} \sim \frac{m_b \tan \beta_b^{\text{eff}}}{v}$, $g_{A\tau\tau} \sim \frac{m_{\tau} \tan \beta_{\tau}^{\text{eff}}}{v}$

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

Searching for neutral Higgs bosons in non-standard channels

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contd...

- Enhanced production and decay modes:

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

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

- In the MSSM the $b\bar{b}$ channel has greater model dependence than $\tau\tau$.  

Carena et.al. ’05
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:

$$
\begin{array}{c}
g \\
\downarrow \\
H/A \\
\downarrow \\
b \\
\end{array}
$$

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

Cao et.al. ’09, Baer et. al. ’11
Signal and Background Simulation

- Simulation used MG5 interfaced with Pythia 6.4.
- QCD background: Separately simulated the $3b+X$ and $2b+j+X$ where $X=1,2j$
- Used $k_t$ matching, with matching scale of 30 GeV.
- Background separation into $bbj$ and $3b$ samples does not model $b$ jets with $p_T$ below $\sim 40$ GeV very well.
- $b$-jets are clustered using anti-$k_T$ with $\Delta R = 0.4$.
- Jet energy smearing of $100%/\sqrt{E/\text{GeV}}$.
- We assume a constant $b$-tagging efficiency of 60%, a $c$-jet mis-tag rate of 10% and a light-jet mis-tag rate of 1%.
- Low mis-tag rate of $c$- and light-jets leads to the $bbj$ and $3b$ backgrounds being comparable.
Selection I vs Selection II

- Selection I: Exactly 3 $b$-tagged jets with $p_T > 60$ GeV and $|\eta| < 2.0$.
- Selection II: Exactly 3 $b$-tagged jets with $p_T^{b_1} > 130$ GeV, $p_T^{b_2,3} > 50$ GeV and $|\eta| < 2.0$.
- Require $M_{12}, M_{13}$ or $M_{23}$ within 25 GeV window of Higgs mass.

For $\tan \beta_{\text{eff}}^b = 30$ @ 30 fb$^{-1}$ 7 TeV LHC

<table>
<thead>
<tr>
<th>$m_A$ (GeV)</th>
<th>Selection I</th>
<th>Selection II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S/B$</td>
<td>$S/\sqrt{B}$</td>
</tr>
<tr>
<td>150</td>
<td>0.06</td>
<td>14.1</td>
</tr>
<tr>
<td>200</td>
<td>0.057</td>
<td>14.4</td>
</tr>
<tr>
<td>300</td>
<td>0.035</td>
<td>7.3</td>
</tr>
<tr>
<td>400</td>
<td>0.027</td>
<td>3.4</td>
</tr>
</tbody>
</table>
Signal and Background Distributions for $\tan \beta = 30$

- Total SM Background
- Signal ($M_{H,A} = 200$ GeV) X 10
- Signal ($M_{H,A} = 300$ GeV) X 10

Events/(25 GeV) vs. $M_{12}$ (GeV)
Reach in the general 2HDM Model
The $3b$ vs $\tau\tau$ in the MSSM
CMS Analysis

CMS preliminary 2.7-4.8 fb$^{-1}$ \(\sqrt{s} = 7\) TeV

HCP Nov. 2012

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Conclusions

- The $A \rightarrow \tau \tau$ LHC search puts weak limits on regions of large $\tan \beta^b_{\text{eff}}$ and small $\tan \beta^\tau_{\text{eff}}$ in 2HDMs.
- The $A/H \rightarrow b\bar{b}$ is a complementary channel that probes parametric scenarios of large $\tan \beta^b_{\text{eff}}$.
- The reach of the $A/H \rightarrow b\bar{b}$ channel is limited by low $S/B$ for low to moderate $\tan \beta^b_{\text{eff}}$, but can be powerful at large $\tan \beta^b_{\text{eff}}$. 
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: $2.1 \text{ fb}^{-1} @ 7 \text{ TeV}$ CMS-PAS-SUS-11-013

<table>
<thead>
<tr>
<th>Selection</th>
<th>$N(\tau)=0$</th>
<th>$N(\tau)=1$</th>
<th>$N(\tau)=2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MET &gt; 50, $H_T &gt; 200$, no Z</td>
<td>$0.003 \pm 0.002$</td>
<td>$0.01 \pm 0.05$</td>
<td>$0.30 \pm 0.22$</td>
</tr>
<tr>
<td>MET &gt; 50, $H_T &gt; 200$, Z</td>
<td>$0.06 \pm 0.04$</td>
<td>$0.13 \pm 0.10$</td>
<td>$0.15 \pm 0.23$</td>
</tr>
<tr>
<td>MET &gt; 50, $H_T &lt; 200$, no Z</td>
<td>$0.014 \pm 0.005$</td>
<td>$0.22 \pm 0.10$</td>
<td>$0.59 \pm 0.25$</td>
</tr>
<tr>
<td>MET &gt; 50, $H_T &lt; 200$, Z</td>
<td>$0.43 \pm 0.15$</td>
<td>$0.91 \pm 0.28$</td>
<td>$0.34 \pm 0.15$</td>
</tr>
<tr>
<td>MET &lt; 50, $H_T &gt; 200$, no Z</td>
<td>$0.0013 \pm 0.0008$</td>
<td>$0.01 \pm 0.05$</td>
<td>$0.18 \pm 0.07$</td>
</tr>
<tr>
<td>MET &lt; 50, $H_T &gt; 200$, Z</td>
<td>$0.28 \pm 0.11$</td>
<td>$0.13 \pm 0.10$</td>
<td>$0.52 \pm 0.19$</td>
</tr>
<tr>
<td>MET &lt; 50, $H_T &lt; 200$, no Z</td>
<td>$0.08 \pm 0.03$</td>
<td>$0.73 \pm 0.20$</td>
<td>$6.9 \pm 3.8$</td>
</tr>
<tr>
<td>MET &lt; 50, $H_T &lt; 200$, Z</td>
<td>$9.5 \pm 3.8$</td>
<td>$5.7 \pm 1.4$</td>
<td>$21 \pm 11$</td>
</tr>
</tbody>
</table>

- CMS 2012: $4.8 \text{ fb}^{-1} @ 7 \text{ TeV}$ arXiv:1204.5341

<table>
<thead>
<tr>
<th>Selection</th>
<th>$N(\tau)=0$</th>
<th>$N(\tau)=1$</th>
<th>$N(\tau)=2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4\ell E_T^{miss} &gt; 50, H_T &gt; 200$, no Z</td>
<td>$0.018 \pm 0.005$</td>
<td>$0.09 \pm 0.06$</td>
<td>$0.7 \pm 0.7$</td>
</tr>
<tr>
<td>$4\ell E_T^{miss} &gt; 50, H_T &gt; 200$, Z</td>
<td>$0.22 \pm 0.05$</td>
<td>$0.27 \pm 0.11$</td>
<td>$0.8 \pm 1.2$</td>
</tr>
<tr>
<td>$4\ell E_T^{miss} &gt; 50, H_T &lt; 200$, no Z</td>
<td>$0.20 \pm 0.07$</td>
<td>$0.59 \pm 0.17$</td>
<td>$1.5 \pm 0.6$</td>
</tr>
<tr>
<td>$4\ell E_T^{miss} &lt; 50, H_T &lt; 200$, Z</td>
<td>$0.79 \pm 0.21$</td>
<td>$2.3 \pm 0.7$</td>
<td>$1.1 \pm 0.7$</td>
</tr>
<tr>
<td>$4\ell E_T^{miss} &lt; 50, H_T &gt; 200$, no Z</td>
<td>$0.006 \pm 0.001$</td>
<td>$0.14 \pm 0.08$</td>
<td>$0.25 \pm 0.07$</td>
</tr>
<tr>
<td>$4\ell E_T^{miss} &lt; 50, H_T &gt; 200$, Z</td>
<td>$0.83 \pm 0.33$</td>
<td>$0.55 \pm 0.21$</td>
<td>$1.14 \pm 0.42$</td>
</tr>
<tr>
<td>$4\ell E_T^{miss} &lt; 50, H_T &lt; 200$, no Z</td>
<td>$2.6 \pm 1.1$</td>
<td>$3.9 \pm 1.2$</td>
<td>$10.6 \pm 3.2$</td>
</tr>
<tr>
<td>$4\ell E_T^{miss} &lt; 50, H_T &lt; 200$, Z</td>
<td>$33 \pm 15$</td>
<td>$17 \pm 5.2$</td>
<td>$62 \pm 16$</td>
</tr>
</tbody>
</table>
Theoretical Implications of Signal

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

- The CMS 2012 multi-lepton data puts limits on $BR(t \rightarrow ch) < 2.7\%$
  
  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 \((A^0_v, A^0_s)\)

\[ \mathcal{L}^\text{Kin}_{\text{Higgs}} \subset -\frac{g_2}{2c_\theta_W} Z^\mu (c_\theta A_1^0 - s_\theta A_2^0) \partial_\mu \left( s_2\beta h^0_v + c_2\beta H^0_v \right) \]

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>$M_{\tilde{q}}$ (TeV)</th>
</tr>
</thead>
<tbody>
<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>
</tr>
<tr>
<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>
</tr>
<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>
</tr>
</tbody>
</table>

<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>
</tr>
</thead>
<tbody>
<tr>
<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>
</tr>
<tr>
<td>BM2</td>
<td>125.1</td>
<td>283</td>
<td>19.7</td>
<td>278</td>
<td>0.984</td>
<td>-0.690</td>
</tr>
<tr>
<td>BM3</td>
<td>124.5</td>
<td>252</td>
<td>117</td>
<td>248</td>
<td>0.992</td>
<td>-0.668</td>
</tr>
</tbody>
</table>
Higgs couplings of Benchmark points

<table>
<thead>
<tr>
<th>$BR$ 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>
</tr>
</thead>
<tbody>
<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>
</tr>
<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>
</tr>
<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>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>$BR$ 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>
</tr>
</thead>
<tbody>
<tr>
<td>BM1</td>
<td>$4.5 \times 10^{-3}$</td>
<td>$5.6 \times 10^{-4}$</td>
<td>0.78</td>
<td>0.17</td>
</tr>
<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>
</tr>
<tr>
<td>BM3</td>
<td>$1.9 \times 10^{-2}$</td>
<td>$1.7 \times 10^{-6}$</td>
<td>0.78</td>
<td>0.19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$BR$ of $A_1^0$</th>
<th>$\tau\tau$</th>
<th>$b\bar{b}$</th>
<th>$gg$</th>
<th>Signal Rate ($\mu$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM1</td>
<td>0.74</td>
<td>0.0</td>
<td>0.12</td>
<td>0.28</td>
</tr>
<tr>
<td>BM2</td>
<td>$5.9 \times 10^{-2}$</td>
<td>0.92</td>
<td>$1.1 \times 10^{-2}$</td>
<td>$5.7 \times 10^{-3}$</td>
</tr>
<tr>
<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>
</tr>
</tbody>
</table>
Event Simulation

- Simulation used Pythia8.170 for $pp$ collisions.
- Include the effects of ISR, FSR, multiple interactions and fragmentation.
- The Z-bosons were allowed to decay only into $e, \mu, \tau$.
- No detector simulator was used, but instead implemented an CMS-like $\tau_h$ reconstruction algorithm.

- Trigger requirements:
  - 1-lepton: muon (electron) has a $p_T > 35 (85)$ GeV
  - 2-lepton: $p_T^1 \geq 20$ GeV and $p_T^2 \geq 10$ GeV.

- Lepton identification: $p_T \geq 8$ GeV and $|\eta| \leq 2.1$.

- Lepton isolation: $I_{\text{Rel}} = E_{\text{cone}} / E_\ell \leq 0.15$, where $E_\ell = \text{energy of lepton}$ and $E_{\text{cone}} = \text{energy in a } \Delta R = 0.3 (0.4)$ for muons (electrons).
\(\tau_h\) reconstruction

- \(\tau_h\) reconstruction: 1-pronged track with \(p_T \geq 8.0\) GeV.
- \(\tau_h\) isolation: \(E_{\text{ann}}/E_{\text{cone}} \leq 0.15\) where,
  \[E_{\text{ann}} = \text{energy in } 0.1 < \Delta R \leq 0.3\]
  \[E_{\text{cone}} = \text{energy in } \Delta R \leq 0.1.\]
\( \epsilon = \frac{\text{Number of events to pass cuts}}{\text{Number of events generated}} \)
Toy-Model for $\tau_h$ reconstruction

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

$\theta_{CM} =$ Angle of $\pi^+$ in rest frame of $A$ 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

- Due to low statistics we assume a Poisson distribution for the number of events.
- We assume the background errors are gaussian.
- The maximum allowed number of signal events at 95% C.L. (\(S_{95}^{\text{Max}}\)) is found by solving:

\[
\int_0^\infty dB \frac{\Gamma(N_{\text{obs}} + 1, S_{95}^{\text{Max}} + B)}{N_{\text{obs}}!} \frac{1}{\mathcal{N}_B} \exp \left[ -\frac{(B - \mu_B)^2}{2\sigma_B^2} \right] = 0.05
\]

- The bounds on \(\sigma_{\text{sig}}\), normalized to \(\sigma_{SM}\) is:

\[
\mu_{95}^i \equiv \frac{S_{95}^{i\text{Max}}}{\sigma_{HSM} \times \mathcal{BR}(Z \rightarrow l^+ l^-) \times \epsilon^i \times \mathcal{L}}
\]
contd.

1-τ_h constraint is the strongest due to large \( \epsilon_1 \tau_h \) and
\[ N_{obs}^{CMS} \sim N_{bkg} \]
H and A Mass reconstruction in the $2\tau h$ channel

- **Transverse Mass:**

$$m^T_A = \sqrt{p_V^2 + 2(E_V E_+^T - p_V^T \cdot p_+^T)}$$

$$m^T_H = \sqrt{(p_V + p_Z)^2 + 2((E_V + E_Z)E_+^T - (p_V^T + p_Z^T) \cdot p_+^T)}$$

where $m^T_i \leq m_i$

Barr et. al., 2009

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

$$\lambda_1 p^T_{V_1} + \lambda_2 p^T_{V_2} = p^T_+.$$

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

Ellis et. al., 1987
The 8 kinematic constraint equations are:

\[ p_{\nu_1}^2 = 0 = p_{\nu_2}^2 \]
\[ (p_{\nu_1} + p_{\nu_1})^2 = m_{\tau}^2 = (p_{\nu_2} + p_{\nu_2})^2 \]
\[ m_A^2 = (p_{\nu_1} + p_{\nu_1} + p_{\nu_2} + p_{\nu_2})^2 \]
\[ m_H^2 = (p_Z + p_{\nu_1} + p_{\nu_1} + p_{\nu_2} + p_{\nu_2})^2 \]
\[ p_{\nu_1}^x + p_{\nu_2}^x = p^x_+ \]
\[ p_{\nu_1}^y + p_{\nu_2}^y = p^y_+ \]

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

Searching for neutral Higgs bosons in non-standard channels
Arjun Menon  University of Oregon
But visible $p_T^{\tau} \geq 20$ GeV $\Rightarrow$ reduced efficiencies.

<table>
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<tr>
<th>Selection</th>
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<th>$N(\tau)=0$, NbJet=0</th>
<th>$N(\tau)=1$, NbJet=0</th>
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<td>OSSF0</td>
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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 $\text{min}(\rho_T)$ 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 $\tau\tau$. 