Search for the exotic decays of the Higgs boson

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We consider a model with an SU(2)$_{\text{L}}$ 
Two doublets - $\phi_1$ and $\phi_2$

$$
\begin{pmatrix}
\Phi_1 \\
\Phi_2
\end{pmatrix}
=
\begin{pmatrix}
\cos \beta & -\sin \beta \\
\sin \beta & \cos \beta
\end{pmatrix}
\begin{pmatrix}
\Phi \\
\Psi
\end{pmatrix}
$$

$\tan \beta = u_2/u_1$  
$u_1^2 + u_2^2 = v^2$

$u_1$ vacuum expectation values (vev) of the neutral component.

Goldstone bosons (NG) boson

$\Phi = 
\begin{bmatrix}
G^+ \\
\frac{1}{\sqrt{2}}(h'_1 + v + iG^0)
\end{bmatrix}$

$\Psi = 
\begin{bmatrix}
H^+ \\
\frac{1}{\sqrt{2}}(h'_2 + iA)
\end{bmatrix}$

CP-even Higgs

CP-odd Higgs

SM-like Higgs with 125 GeV
Two Higgs Doublet Models (2HDM)

The 2HDM Lagrangian for $\Phi_i$

$$L = \sum_i \left| D_\mu \Phi_i \right|^2 - V(\Phi_1, \Phi_2) + L_{yuk}$$

Kinetic term for the two Higgs doublets

The 2HDM potential

$$V(\Phi_1, \Phi_2) = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + h.c.) + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2$$

$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2} \lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + h.c.] .$$

After EW symmetry breaking, the physical scalar spectrum of five states:

1) Two CP-even Higgs $h, H$ with $m_h < m_H$, can be SM-like
2) CP-odd scalar $A$
3) Charge scalar pair $H^\pm$

Three of these are absorbed by and given mass to the $W^\pm$ and $Z$ boson
Interpretation with 2HDM

Parameters in the **physical basis**: \( m_h = 125 \text{ GeV} \) in our case

- \( m_h, m_H, m_A, m_{H^\pm}, \tan \beta, \sin(\beta - \alpha), v, m_{12}^2 \)

**Mass of bosons**

**The ratio of Vacuum expectation values.**

**Potential parameter**

**The mixing angle between cp-even boson**

4 types of 2HDM: different ways to couple \( \phi_1 \) and \( \phi_2 \) to fermions

- **Type I**: All quarks and leptons couple to only one scalar doublet \( \phi_2 \).
- **Type 2**: MSSM-like, \( d_R \) and \( e_R \) couple to \( \phi_1 \), \( u_R \) to \( \phi_2 \).
- **Type 3 (lepton specific)**: all quarks couple to \( \phi_2 \), leptons couple to \( \phi_1 \).
- **Type 04 (flipped)**: with \( u_R, e_R \) coupling to \( \phi_2 \) and \( d_R \) to \( \phi_1 \).

<table>
<thead>
<tr>
<th></th>
<th>Type I</th>
<th>Type II</th>
<th>Flipped (Type Y)</th>
<th>Lepton Specific (Type X)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up-type quark</td>
<td>( \phi_2 )</td>
<td>( \phi_2 )</td>
<td>( \phi_2 )</td>
<td>( \phi_2 )</td>
</tr>
<tr>
<td>Down-type quark</td>
<td>( \phi_2 )</td>
<td>( \phi_1 )</td>
<td>( \phi_1 )</td>
<td>( \phi_2 )</td>
</tr>
<tr>
<td>Leptons</td>
<td>( \phi_2 )</td>
<td>( \phi_1 )</td>
<td>( \phi_2 )</td>
<td>( \phi_1 )</td>
</tr>
</tbody>
</table>
Add to the 2HDM one complex scalar singlet $S$, which has a small mixing with $\Phi_1$ and $\Phi_2$.

This leads to two additional singlet states (CP-even scalar $s$ and CP-odd $\alpha$) which inherit interactions to the SM fermions from their mixing with the Higgs doublets.

The general 2HDM+S model generates a large variety of Higgs decay phenomenology:

$$h \rightarrow \alpha\alpha \rightarrow X\bar{X}YY, \quad h \rightarrow ss \rightarrow X\bar{X}YY, \quad \text{and} \quad h \rightarrow \alpha Z \rightarrow X\bar{X}YY$$

Four types of 2HDM+S forbid flavor changing neutral currents (FCNC) at tree level.

- **Type 1**: all SM particles couple to the first doublet.
- **Type 2**: leptons and down-type quarks couple to the second doublet, whereas up-type quarks couple to the first doublet. The next-to-minimal supersymmetric model (NMSSM) is a particular case of 2HDM+S that brings a solution to the $\mu$ problem.
- **Type 3**: leptons couple to the second doublet, and quarks to the first one.
- **Type 04**: down-type quarks couple to the second doublet while leptons and up-type quarks couple to the first doublet.
Channels investigated

Dimitra Tsiakkouri

\[ h(125) \rightarrow \alpha \alpha \rightarrow b\bar{b}\tau^+\tau^- \]

\( \begin{cases} 
    b\bar{b} + e\tau_h, \\
    b\bar{b} + \mu\tau_h, \\
    b\bar{b} + e\mu 
\end{cases} \)

\( \begin{cases} 
    b\bar{b} + \tau_h\tau_h, \\
    b\bar{b} + \mu\mu, \\
    b\bar{b} + ee 
\end{cases} \)

low signal acceptance due to trigger threshold (at least \( p_T > 40 \) GeV offline for each \( \tau_h \))

are discarded due to small branching fraction

Eleni Irodotou

\[ h(125) \rightarrow \alpha \alpha \rightarrow \tau^+\tau^-\mu^+\mu^- \]

\( \begin{cases} 
    \mu\mu + e\mu, \\
    \mu\mu + e\tau_h, \\
    \mu\mu + \mu\tau_h, \\
    \mu\mu + \tau_h\tau_h 
\end{cases} \)

\( \begin{cases} 
    \mu\mu + ee, \\
    \mu\mu + \mu\mu 
\end{cases} \)

Are not considered, small BR and large irreducible background
Channels investigated

Aimilios Ioannou

\[ A \rightarrow Zh \rightarrow \ell^+ \ell^- b\bar{b} \left\{ eeb\bar{b}, \mu\mu b\bar{b} \right\} \]

Ioannis Vasilas

\[ A \rightarrow Zh \rightarrow \ell^+ \ell^- \tau^+ \tau^- \left\{ ee\tau_h \tau_h, eee\mu, eee\tau_h, ee\mu\tau_h, \mu\mu\tau_h, \mu\mu\epsilon \mu, \mu\mu\epsilon \tau_h, \mu\mu\mu\tau_h \right\} \]

Are not considered, small BR and large irreducible background
### Channels investigated

\[ h \rightarrow \alpha \alpha \rightarrow \tau^+ \tau^- \tau^+ \tau^- \]

\[ h \rightarrow \alpha \alpha \rightarrow b\bar{b} \mu^+ \mu^- \]

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Branching ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau^- \rightarrow \mu^- \bar{v}<em>\mu v</em>\tau )</td>
<td>17.41</td>
</tr>
<tr>
<td>( \tau^- \rightarrow e^- \bar{v}<em>e v</em>\tau )</td>
<td>17.83</td>
</tr>
<tr>
<td>( \tau^- \rightarrow l^- \bar{v}<em>l v</em>\tau )</td>
<td>35.24</td>
</tr>
<tr>
<td>( \tau^- \rightarrow \pi^- v_\tau )</td>
<td>11.53</td>
</tr>
<tr>
<td>( \tau^- \rightarrow \pi^- \pi^0 v_\tau )</td>
<td>25.95</td>
</tr>
<tr>
<td>( \tau^- \rightarrow \pi^- \pi^0 v_\tau )</td>
<td>9.53</td>
</tr>
<tr>
<td>( \tau^- \rightarrow \pi^- \pi^+ \pi^- v_\tau )</td>
<td>4.80</td>
</tr>
<tr>
<td>( \tau^- \rightarrow \pi^- \pi^+ \pi^- \pi^0 v_\tau )</td>
<td>9.80</td>
</tr>
<tr>
<td>Other modes with hadrons</td>
<td>3.15</td>
</tr>
<tr>
<td>All hadronic modes</td>
<td>64.76</td>
</tr>
</tbody>
</table>
The benchmark points

\[ h \rightarrow \alpha \alpha \rightarrow b \bar{b} \tau^+ \tau^- \]

final state with good sensitivity because of the large branching fractions to \( \tau \) and \( b \) quarks in most models.

\[ Br(a \rightarrow \tau^+ \tau^-) = 6\% \]
\[ Br\left(a \rightarrow b \bar{b}\right) = 94\% \]

\[ 2m_b < m_{\alpha} < m_{h/2} \]
The benchmark points

\[ h \rightarrow \alpha \alpha \rightarrow \mu^+ \mu^- \tau^+ \tau^- \]

\((2m_\tau < m_\alpha < m_{h/2})\)

\[ Br(\alpha \rightarrow \tau^+ \tau^-) \approx 100\% \]

\[ Br(\alpha \rightarrow \mu^+ \mu^-) = 0.35\% \]
The ATLAS collaboration reported a small deviation on the search channel $A \rightarrow Zh$: an excess, relative to background expectations, of 0.1-0.3 pb for $\sigma(A \rightarrow Zh)BR(h \rightarrow b\bar{b})$, for a potential pseudoscalar mass of about 440 GeV.
The benchmark points

$A \rightarrow Zh \rightarrow \ell^+ \ell^- \tau^+ \tau^-$

<table>
<thead>
<tr>
<th>$m_h$</th>
<th>$m_H$</th>
<th>$m_A$</th>
<th>$m_{H^\pm}$</th>
<th>$\sin(\beta - \alpha)$</th>
<th>$\tan \beta$</th>
<th>$m_{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>125 GeV</td>
<td>300 GeV</td>
<td>300 GeV</td>
<td>400 GeV</td>
<td>0.6</td>
<td>2</td>
<td>100 GeV</td>
</tr>
</tbody>
</table>

$Br(A \rightarrow Zh) = 98.4\%$

$Br(h \rightarrow \tau^+ \tau^-) = 6.8\%$
The benchmark points

\[ h \rightarrow \alpha\alpha \rightarrow b\bar{b} \mu^+ \mu^- \]

In 2HDM+S Type 3 the branching fractions of the \( h \rightarrow \alpha\alpha \) channel is 10% with \( \tan \beta = 2 \).

\[ 2 \times Br(\alpha \rightarrow b\bar{b}) Br(\alpha \rightarrow \mu^+ \mu^-) = 1.7 \times 10^{-3} \]
The benchmark points

\( h \rightarrow \alpha \alpha \rightarrow \tau^+ \tau^- \tau^+ \tau^- \)

The branching ratios to lepton pairs are in proportion

\( \tau^+ \tau^- : \mu^+ \mu^- : e^+ e^- \approx 1 : 3.5 \times 10^{-3} : 8 \times 10^{-8} \)

\( m_\alpha = [2m_\tau, m_{h/2}] \)
Background Processes

\[ h \to aa \to 4\tau, \quad h \to aa \to 2\tau 2\mu \]

- **ZZjj and WZjj production**: The production of two vector bosons in association with two jets is the main background processes for this channel.

- **tt(bar) production**: Two leptons or hadrons and neutrino that produce missing momentum can originate from the decays of the two \( W \) bosons. The third lepton/hadron and an additional neutrino can be produced in the decay of a bottom quark (for the case of 4 taus).

- **Ztt(bar) and Wtt(bar) production**: In these processes an additional vector boson is produced, in association with a top quark pair.

- **Zbb(bar) and Wbb(bar) production**: One or two leptons can originate from the decays of the vector bosons. One or even two leptons can then be produced in the \( b \)-quark decays.

- **QCD**: Potential background is caused by events containing misidentified leptons or leptons from \( b \) meson decays.
Background Processes

$h \rightarrow aa \rightarrow 2\tau 2\mu, h \rightarrow aa \rightarrow 2b2\mu$

- **Drell–Yan production of** $Z \rightarrow \tau^+ \tau^-$: In the $e \tau_h$ channel, $Z \rightarrow \tau^+ \tau^-$ production is also an important source of background because of the 2–3% probability for electrons to be misidentified as electron is misidentified as $\tau_h$.

- **$W +$ jets samples:** $W$ boson decays leptonically and a jet is misidentified as $\tau_h$.

- **ttbar + Single top:** is one of the main backgrounds in the $e\mu$ channel.

- $WZ^*/\gamma^*(\rightarrow \tau^+ \tau^-)b\bar{b}$: has the $b\bar{b}$ pairs from a virtual gluon splitting, the $\tau^+ \tau^-$ pair from an intermediate $Z^*/\gamma^*$ and the charged lepton plus missing energy from $W$ boson.

- **Diboson production** ($WW$, $ZZ$, and $WZ$):

- **Reducible background** arises from jets misidentified as $b$-quarks, or as hadronically decaying taus.
Background Processes

$A \rightarrow Zh \rightarrow \ell^+ \ell^- b\bar{b}$

- **Z + jets:** The production of single $Z/g$ bosons in association with one or more partons or gluons in the final state is topologically similar to the searched signal.

- **W + jets:** The leptonic decay of a W boson can be an irreducible background in the single-lepton channel, or in the zero-lepton channel in the case the charged lepton escapes undetected or fails the lepton identification requirements.

- **$tt$:** These events always contain two energetic b-jets and two W bosons which may decay to high $p_T$, isolated leptons.

- **single-top:**

- **Diboson ($W W$, $W Z$, $Z Z$):** the production of two vector bosons in the SM is a rare process, with a similar kinematics to that of the signal. Furthermore, the boost of the bosons could be large.

- **multijet (QCD):** despite its enormous cross section at LHC, the probability to produce final states with prompt, isolated leptons or large missing transverse momentum is very low.
Background Process

\[ A \rightarrow Zh \rightarrow \ell^+ \ell^- \tau^+ \tau^- \]

- **WZ+jets**: Misidentified light leptons arise from semileptonic decays of heavy flavor quarks, decays in flight of hadrons, and photon conversions, while jets originating from quarks or gluons can be misidentified as \(\tau_h\).

- **Z+jets**: The Z+jets background is characterised by a softer lepton transverse momentum spectrum than the signal one, this background is reduced.

- **tt+jets**: It will be assumed that top quarks decay only SM-like, i.e. via \(t \rightarrow Wb\). Two leptons or hadrons and neutrino that produce missing momentum can originate from the decays of the two \(W\) bosons. The tagging jets can be faked by \(b\)-jets that are misidentified as light jets, or by jets from additional gluon radiation in the event.

- **Diboson production (WW, ZZ, and WZ)**: The background is dominated by \(ZZ^*\) production with \(Z \rightarrow ee/\mu\mu\) decays

- **tW**: There are two \(W\) produced in the \(tW \rightarrow bWW\) process. This background is similar to that of the di-boson processes.
Results

Expected Limits on $\sigma_h/\sigma_{SM} \times BR( h(125) \rightarrow \alpha\alpha \rightarrow 2\mu2\tau )$

Upper limits at 95% CL on $\sigma_h/\sigma_{SM} \times BR( h(125) \rightarrow \alpha\alpha )$ for masses of $\alpha$ between 15 and 62.5 GeV are as low as $1.2 \times 10^{-4}$. 
Upper limits on $\sigma_h/\sigma_{SM} \times \text{BR}(h \rightarrow \alpha\alpha)$ in the different 2HDM+S models

The most stringent limits are obtained in 2HDM+S type III at large $\tan \beta$, where the couplings to leptons are enhanced, and where limits as low as about 1% can be set.
Results

Expected Limits on $\sigma_h/\sigma_{SM} \times \text{BR}(h(125) \rightarrow \alpha\alpha \rightarrow 2b2\tau)$

Upper limits at 95% CL on $\sigma_h/\sigma_{SM} \times \text{B}(h \rightarrow \alpha\alpha)$ are range from 4 to 12% over the pseudoscalar mass range between 15 and 60 GeV.

The combined limit at intermediate mass is about 3.5%
Expected Limits on $\frac{\sigma_h}{\sigma_{SM}} \times \text{BR}(h \rightarrow \alpha\alpha)$ for all types of 2HDM+S

- In the scenario with the highest branching fraction, 2HDM+S type-3 with $\tan \beta = 2$, the expected limit is as low as 6% for $m_\alpha = 35$ GeV.

- The Higgs boson pair production rate $\frac{\sigma_h}{\sigma_{SM}} \times \text{BR}(h \rightarrow \alpha\alpha)$ for all types of 2HDM+S depends on $\tan \beta$. 
Expected and observed 95% CL limits on $\sigma_h/\sigma_{SM} \times \text{BR } h(\to \alpha\alpha)$ in 2HDM+S type III for $\tan \beta = 5$. 

![Graph showing expected and observed 95% CL limits on $\sigma_h/\sigma_{SM} \times \text{BR } h(\to \alpha\alpha)$ in 2HDM+S type III for $\tan \beta = 5$. The graph includes CMS Preliminary data with expected and observed limits for different channels such as $h\to aa, \mu\mu\mu$, $h\to aa, \tau\tau\tau$, $h\to aa, \mu bb$, $h\to aa, \mu\tau\tau$, and $h\to aa, \tau\tau bb$ at 8 TeV and 13 TeV. The limits are displayed for the mass range of $m_a$ (GeV).}
Expected Limits on $\sigma_A \times BR( A \rightarrow Zh) \times BR( h \rightarrow b\bar{b} )$

Gluon-gluon fusion

b-quark associated

The observed $\sigma_{ggA} \cdot BR_{bb}$ exclusion limits are 0.012–0.8 pb

The observed $\sigma_{bqA} \cdot BR_{bb}$ exclusion limits are 0.012–0.7 pb
- The exclusion region in the cos(\(\beta-\alpha\)) versus tan\(\beta\) for \(m_A = 300\) GeV for two 2HDM models.
- The newly discovered Higgs boson (\(m_A = 125\) GeV), is actually the lighter one of the CP-even Higgs bosons predicted by 2HDMs.
- Another assumption made: \(m_A = m_H = m_{H^\pm}\)
- The potential parameter which softly breaks \(Z_2\) symmetry is chosen as: 
  \[ m_{12}^2 = m_A^2 \frac{\tan \beta}{1 + \tan^2 \beta} \]
Summary

- No significant excess of data is observed above the expected SM background, upper limits at 95% CL are set on $\sigma_h/\sigma_{SM} \times BR(h(125) \rightarrow \alpha\alpha \rightarrow 2\mu2\tau)$ for the pseudoscalar masses between 15 and 62.5 GeV.

- No excess of events is found on top of the expected SM background. Upper limits are set on $B(h \rightarrow \alpha\alpha \rightarrow 2b2\tau)$. They range from 4 to 12% over the pseudoscalar mass range between 15 and 60 GeV. This corresponds to upper limits on $B(h \rightarrow aa)$ between 6 and 26% in the most favorable 2HDM+S scenario (namely 2HDM+S type-3 with $\tan b = 2$).

- No signal is observed in the search for a pseudoscalar Higgs boson. Upper limits are set at the 95% CL for $\sigma_A \times BR(A \rightarrow Zh) \times BR(h \rightarrow b\bar{b})$ of $0.012 - 0.80$ pb in the range of $m_A = 220 - 1000$ GeV.
Thank you