Pair production of charged and neutral Higgs bosons at CLIC

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Theoretical background

In the Standard Model, one complex scalar doublet is responsible for the electroweak gauge symmetry breaking, and there is thus only one physical Higgs boson $h^0$.

In several extensions of the Standard Model, and in particular the MSSM, the Higgs sector consists of two complex scalar doublets and there are five Higgs bosons.

- two CP-even neutral $h^0$ and $H^0$,
- one CP-odd neutral $A^0$,
- two charged $H^+$ and $H^-$.

In addition to the four Higgs masses, there are also two additional parameters:

- the ratio $\tan\beta$ of the vacuum expectation values of the two neutral Higgs fields,
- the mixing angle $\alpha$ in the neutral CP-even sector.

In the MSSM, only two parameters are independent, in general they are chosen to be $m_A$ and $\tan\beta$.

AIM OF THE STUDY: estimate the discovery reach for new heavy charged and neutral Higgs bosons at CLIC + accurate measurements of $m_A$ and $\tan\beta$. 
Cross section calculations

Two processes of interest: \( e^+e^- \rightarrow H^+H^- \) and \( e^+e^- \rightarrow A^0H^0 \).

At tree level, very good agreement between PYTHIA simulations and analytical calculations.

At CLIC, one must take into account the high-energy beam-beam effects in the calculation of the cross-section, and in particular the luminosity spectrum after including beamstrahlung.

In the following, we consider an integrated luminosity of 3000 fb\(^{-1}\).
Possible final states

- $e^+ e^- \rightarrow H^+ H^-$

The charged Higgs bosons can decay into fermions pairs, i.e. $tb$ or $\tau \nu$. Generally, $H^\pm \rightarrow tb$ is the dominant decay mode.

- $e^+ e^- \rightarrow A^0 H^0$

The neutral Higgs bosons generally decay into $tt$, $bb$ or $\tau\tau$.

Note: only standard decays are considered in this study!
Reconstruction of $e^+e^- \rightarrow A^0 H^0 \rightarrow bbbb$

At large $\tan\beta$, neutral Higgs bosons mostly decay into $bb$ pairs, so the final state of interest generally consists of 4 $b$ tagged jets.

- there are three ways to combine 4 $b$-jets into 2 $bb$ pairs,
- choose the combination with the smallest difference between the two $bb$ invariant masses,
- apply a mass constrained kinematical fit in order to improve the resolution.

Here, $m_A = 876$ GeV, the hadronic background is integrated over 15 bunch crossings, and the $b$ tagging efficiency is set to 90%.
Reconstruction of $e^+e^- \rightarrow A^0H^0 \rightarrow tttt$

At small $\tan\beta$, neutral Higgs bosons mostly decay into $tt$ pairs, so the final state of interest generally consists of $tttt$, i.e. 4 $b$ tagged jets and 8 non-$b$ tagged jets coming from $W$ bosons which decayed hadronically.

- test the presence of four $W$ bosons decaying hadronically,
- reconstruct each $t$ quark from a $W$ candidate paired with one $b$ tagged jet,
- reconstruct $A$ and $H$ by combining four $t$ candidates into two $tt$ pairs (for this purpose, the combination with the smallest mass difference is chosen),
- apply a mass constrained kinematical fit in order to improve the resolution.

Here, $m_A = 576$ GeV, the hadronic background is integrated over 15 bunch crossings, and the $b$ tagging efficiency is set to 90%.
Reconstruction of $e^+e^- \rightarrow A^0 H^0 \rightarrow tbtb$

For intermediate values of $\tan\beta$, neutral Higgs bosons may decay into $tt$ or $bb$ pairs, so one possible final state consists of $tbtb$, i.e. 4 $b$ tagged jets and 4 non-$b$ tagged jets coming from $W$ bosons which decayed hadronically.

- test the presence of two $W$ bosons decaying hadronically,
- reconstruct each $t$ quark from a $W$ candidate paired with one $b$ tagged jet,
- reconstruct the neutral Higgs bosons by pairing respectively the two $t$ candidates and the two remaining $b$ tagged jets,
- apply cuts on the $tt$, $bb$ and $tb$ invariant masses to distinguish between charged and neutral Higgs bosons pair production,
- apply a mass constrained kinematical fit in order to improve the resolution.

Here, $m_A = 736$ GeV, the hadronic background is integrated over 15 bunch crossings, and the $b$ tagging efficiency is set to 90%.
Reconstruction of $e^+e^- \rightarrow H^+H^- \rightarrow tbtb$

After the pair production of charged Higgs bosons, the final state generally consists of $tbtb$, i.e. 4 $b$ tagged jets and 4 non-$b$ tagged jets coming from hadronic decays of 2 $W$ bosons.

- test the presence of two $W$ bosons decaying hadronically,
- reconstruct each $t$ quark from a $W$ candidate paired with one $b$ tagged jet,
- reconstruct each charged Higgs boson from one $t$ candidate paired with one of the two remaining $b$ tagged jets,
- apply cuts on the $tt$, $bb$ and $tb$ invariant masses to distinguish between charged and neutral Higgs bosons pair production,
- apply a mass constrained kinematical fit in order to improve the resolution.

Here, $m_A = 736$ GeV, the hadronic background is integrated over 15 bunch crossings, and the $b$ tagging efficiency is set to 90%.
Discovery potential at CLIC

The most significant Standard Model background processes are those leading to genuine $bbbb$, $tttt$ or $tbtb$ final states. A careful analysis with CompHEP shows that quark-antiquark pairs usually come from a virtual $\gamma/Z$ boson, a gluon or a light Higgs boson.

For the $A^0 H^0$ signal, $tt$ or $bb$ pairs come from 2 heavy objects having the same mass: the topology is thus very different from the Standard Model background, which is easily reduced. For the $H^+ H^-$ signal, the Standard Model background can be reduced as well, but not as efficiently as for $A^0 H^0$.

Charged Higgs sector:
Discovery up to 1.25 TeV (1.21 TeV) for small (large) $\tan\beta$.

Neutral Higgs sector:

Here, the integrated luminosity is $3000 \text{ fb}^{-1}$.
Discovery limits vs b-tagging

Many processes, such as $W$ boson or $t$ quark pair production, lead to multi-fermions final states, with two or less $b$ quarks. Cuts on the jet multiplicity, the masses of the intermediate states and the number of $b$ jets should allow good reduction (suppression) of these backgrounds. But, one may need to accept a reduction of the $b$-tagging efficiency to better control the non-$b$ jet misidentification rate.

Having assumed no contribution from the background processes with two or less $b$ quarks, the discovery limits at small and large $\tan\beta$ were estimated as a function of the $b$ tagging efficiency.

<table>
<thead>
<tr>
<th>$b$ tagging efficiency</th>
<th>90%</th>
<th>80%</th>
<th>70%</th>
<th>60%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$-jet misidentification rate</td>
<td>45%</td>
<td>20%</td>
<td>10%</td>
<td>4%</td>
</tr>
<tr>
<td>$uds$-jet misidentification rate</td>
<td>20%</td>
<td>7%</td>
<td>0.5%</td>
<td>0.2%</td>
</tr>
<tr>
<td>$H^+ H^-,$ discovery, small $\tan\beta$ (TeV)</td>
<td>1.25</td>
<td>1.22</td>
<td>1.18</td>
<td>1.12</td>
</tr>
<tr>
<td>$H^+ H^-,$ discovery, large $\tan\beta$ (TeV)</td>
<td>1.21</td>
<td>1.17</td>
<td>1.12</td>
<td>1.06</td>
</tr>
<tr>
<td>$A^0 H^0,$ discovery, small $\tan\beta$ (TeV)</td>
<td>1.16</td>
<td>1.07</td>
<td>0.97</td>
<td>0.81</td>
</tr>
<tr>
<td>$A^0 H^0,$ discovery, large $\tan\beta$ (TeV)</td>
<td>1.39</td>
<td>1.34</td>
<td>1.28</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Discovery limit up to 1 TeV and beyond, for all values $\tan\beta$: better than LHC!!
Precision measurements

The mass and the signal rate were estimated by comparing samples of "real" and "simulated" event samples, in terms of $\chi^2$.

<table>
<thead>
<tr>
<th>$m_A$ (in GeV)</th>
<th>576</th>
<th>736</th>
<th>876</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^- \rightarrow H^+H^- \rightarrow tbtb$ (1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta(\sigma \cdot Br^2)/(\sigma \cdot Br^2)$</td>
<td>3.6%</td>
<td>4.9%</td>
<td>5.6%</td>
</tr>
<tr>
<td>$\delta m/m$</td>
<td>0.4%</td>
<td>0.7%</td>
<td>0.9%</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow A^0H^0 \rightarrow bbbb$ (2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta(\sigma \cdot Br^2)/(\sigma \cdot Br^2)$</td>
<td>3.3%</td>
<td>4.7%</td>
<td>6.2%</td>
</tr>
<tr>
<td>$\delta m/m$</td>
<td>0.4%</td>
<td>0.4%</td>
<td>0.4%</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow A^0H^0 \rightarrow tttt$ (3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta(\sigma \cdot Br^2)/(\sigma \cdot Br^2)$</td>
<td>7.5%</td>
<td>10.0%</td>
<td>15.3%</td>
</tr>
<tr>
<td>$\delta m/m$</td>
<td>1.2%</td>
<td>1.8%</td>
<td>2.7%</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow A^0H^0 \rightarrow tbtb$ (4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta(\sigma \cdot Br^2)/(\sigma \cdot Br^2)$</td>
<td>10.2%</td>
<td>13.4%</td>
<td>20.2%</td>
</tr>
<tr>
<td>$\delta m/m$</td>
<td>1.6%</td>
<td>2.1%</td>
<td>2.7%</td>
</tr>
</tbody>
</table>

(1) $\text{Br}(H^\pm \rightarrow tb) = 100\%$
(2) $\text{Br}(A^0/H^0 \rightarrow bb) = 87\%$
(3) $\text{Br}(A^0/H^0 \rightarrow tb) = 100\%$
(4) $\text{Br}(A^0/H^0 \rightarrow bb) = \text{Br}(A^0/H^0 \rightarrow bb) \simeq 46\%$

Here, the integrated luminosity is 3000 fb$^{-1}$.
Determination of $\tan\beta$

Let us define $r = \sqrt{\frac{\text{Br}(H^0 \to bb) \cdot \text{Br}(A^0 \to bb)}{\text{Br}(H^0 \to tt) \cdot \text{Br}(A^0 \to tt)}}$.

The error on $r$ can be written as:

$$\delta r = \frac{r}{2} \sqrt{\left(\frac{\delta (\sigma \cdot \text{Br}^2)}{\sigma \cdot \text{Br}^2}ight)_{bbbb}^2 + \left(\frac{\delta (\sigma \cdot \text{Br}^2)}{\sigma \cdot \text{Br}^2}\right)_{tttt}^2}.$$

Knowing how $r$ depends on $\tan\beta$ and the statistical errors for the signal rate of $e^+e^- \to A^0 H^0 \to bbbb$ and $e^+e^- \to A^0 H^0 \to tttt$ at various values of $\tan\beta$, one can estimate the absolute error $\delta \tan\beta$.

$\to \tan\beta$ can be determined with a relative error of less than 20% (respectively 10%) in the 3-13 (respectively 4-10) range.
Conclusion

New charged and neutral Higgs bosons appear in several extensions of the Standard Model, including Supersymmetry. LHC is likely to discover these new particles up to masses of a few hundred GeV... however not in the whole MSSM phase space, and in particular not in the intermediate $\tan\beta$ range.

CLIC will extend the LHC discovery reach to Higgs masses beyond 1 TeV and all values of $\tan\beta$ should be accessible.

Precision measurements can be performed with a $\chi^2$-analysis. The Higgs mass $m_A$ can be measured with a precision of about 1%. In the 4-10 range, $\tan\beta$ can be determined with a good accuracy (10% or less).

Outlooks: combine the charged and neutral sectors into one single analysis, and consider the influence of decays into supersymmetric particles.