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 α in the neutral CP-even sector.

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

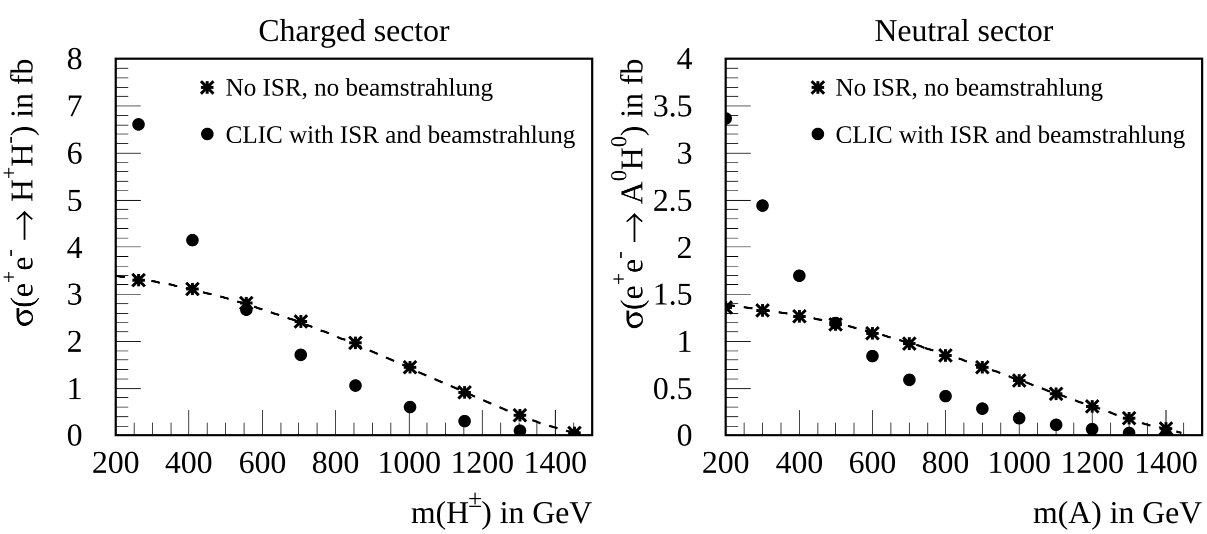
AIM OF THE STUDY: estimate the discovery reach for new heavy charged and neutral Higgs bosons at CLIC + accurate measurements of m_A and $tan\beta$.

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.

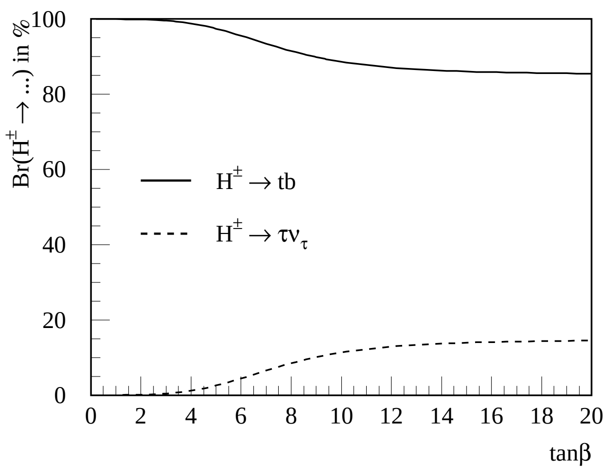


In the following, we consider an integrated luminosity of 3000 fb^{-1}.

Possible final states

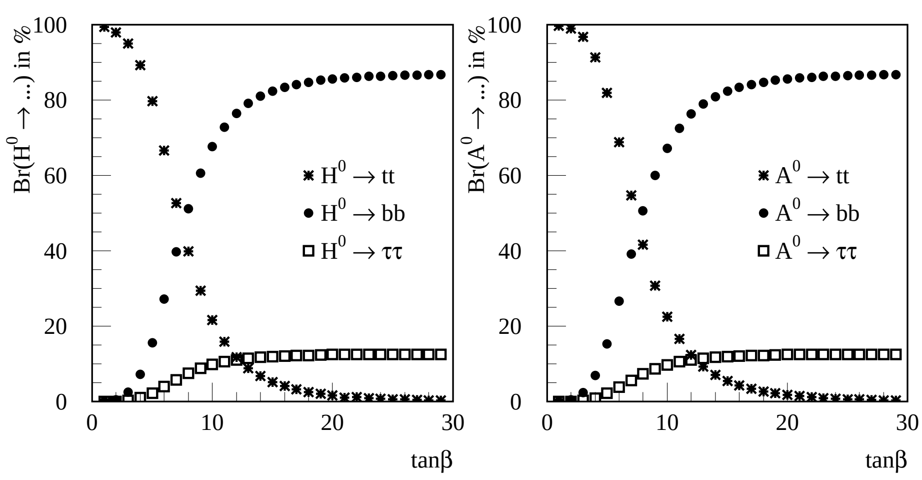
- $e^+e^- \to H^+H^-$

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



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

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

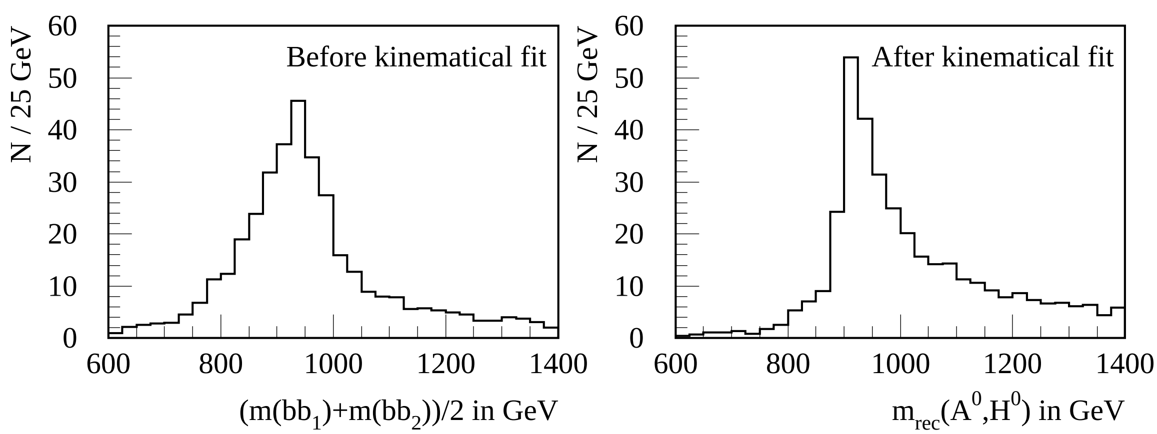


Note: only standard decays are considered in this study!

Reconstruction of $e^+e^- \rightarrow A^0H^0 \rightarrow bbbb$

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.

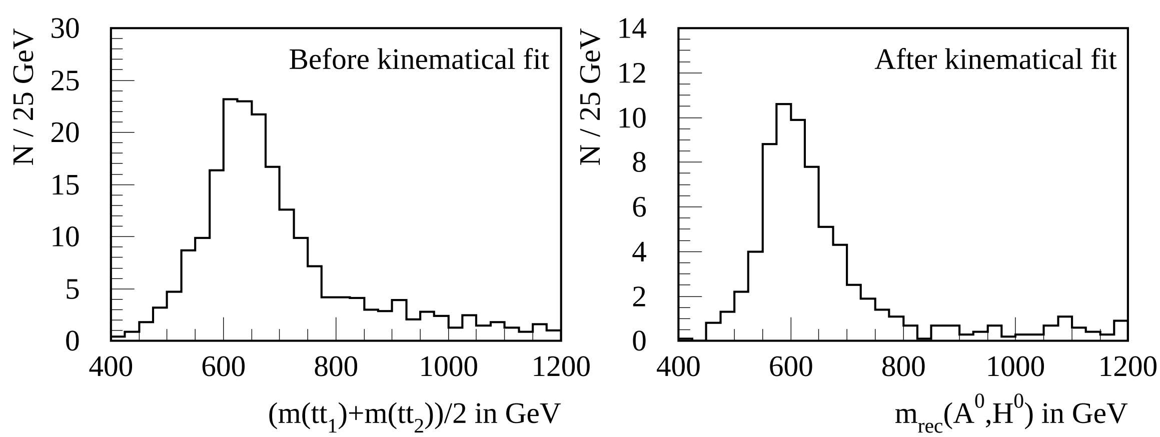


Here, m_A = 876 GeV, the hadronic background is integrated over 15 bunch crossings, and the b tagging efficiency is set to 90%.

Reconstruction of $e^+e^- \to A^0H^0 \to tttt$

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.

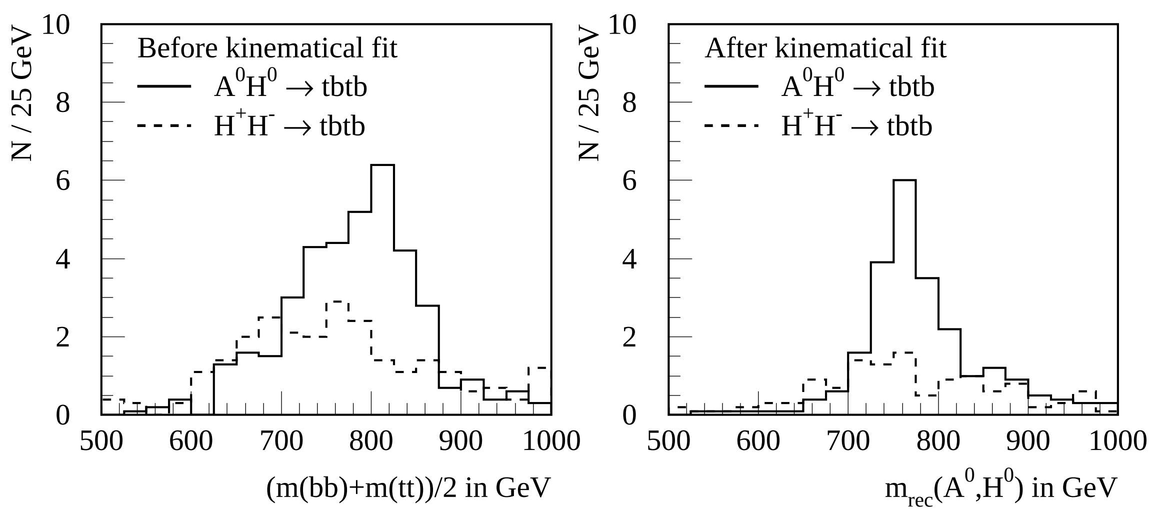


Here, m_A = 576 GeV, the hadronic background is integrated over 15 bunch crossings, and the b tagging efficiency is set to 90%.

Reconstruction of $e^+e^- \rightarrow A^0H^0 \rightarrow tbtb$

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.

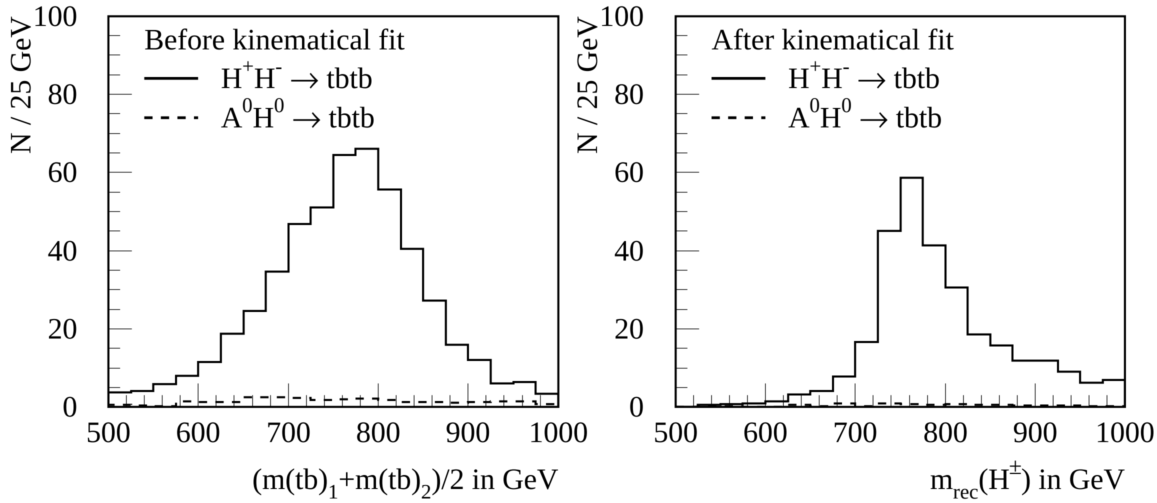


Here, m_A = 736 GeV, the hadronic background is integrated over 15 bunch crossings, and the b tagging efficiency is set to 90%.

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%.

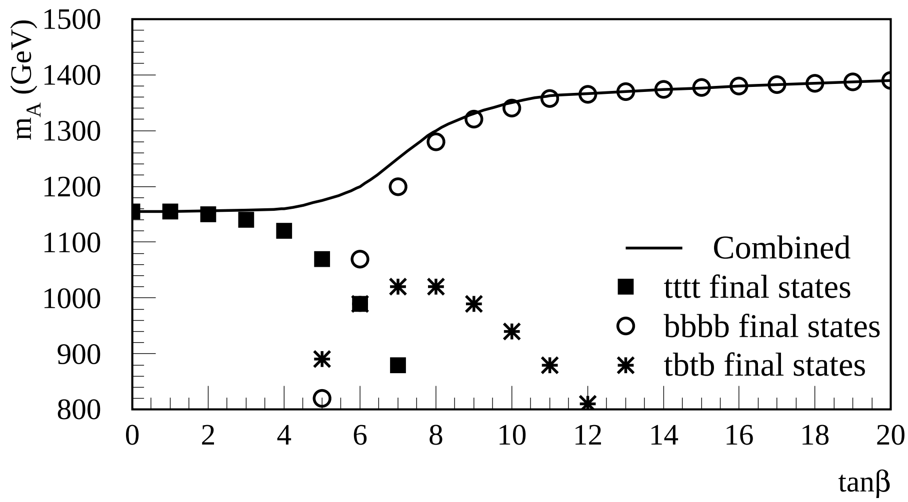
Discovery potential at CLIC

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 γ/Z boson, a gluon or a light Higgs boson.

For the A^0H^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^0H^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 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.

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

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 χ^2.

m_A (in GeV)	576	736	876
$e^+e^- \longrightarrow H^+H^- \longrightarrow tbtb$ (1)			
$\delta(\sigma \cdot \mathrm{Br}^2)/(\sigma \cdot \mathrm{Br}^2)$	3.6%	4.9%	5.6%
$\delta m/m$	0.4%	0.7%	0.9%
$e^+e^- \longrightarrow A^0H^0 \longrightarrow bbbb$ (2)			
$\delta(\sigma \cdot \mathrm{Br}^2)/(\sigma \cdot \mathrm{Br}^2)$	3.3%	4.7%	6.2%
$\delta m/m$	0.4%	0.4%	0.4%
$e^+e^- \longrightarrow A^0H^0 \longrightarrow tttt$ (3)			
$\delta(\sigma \cdot \mathrm{Br}^2)/(\sigma \cdot \mathrm{Br}^2)$	7.5%	10.0%	15.3%
$\delta m/m$	1.2%	1.8%	2.7%
$e^+e^- \longrightarrow A^0H^0 \longrightarrow tbtb$ (4)			
$\delta(\sigma \cdot \mathrm{Br}^2)/(\sigma \cdot \mathrm{Br}^2)$	10.2%	13.4%	20.2%
$\delta m/m$	1.6%	2.1%	2.7%

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

Here, the integrated luminosity is 3000 fb^{-1}.

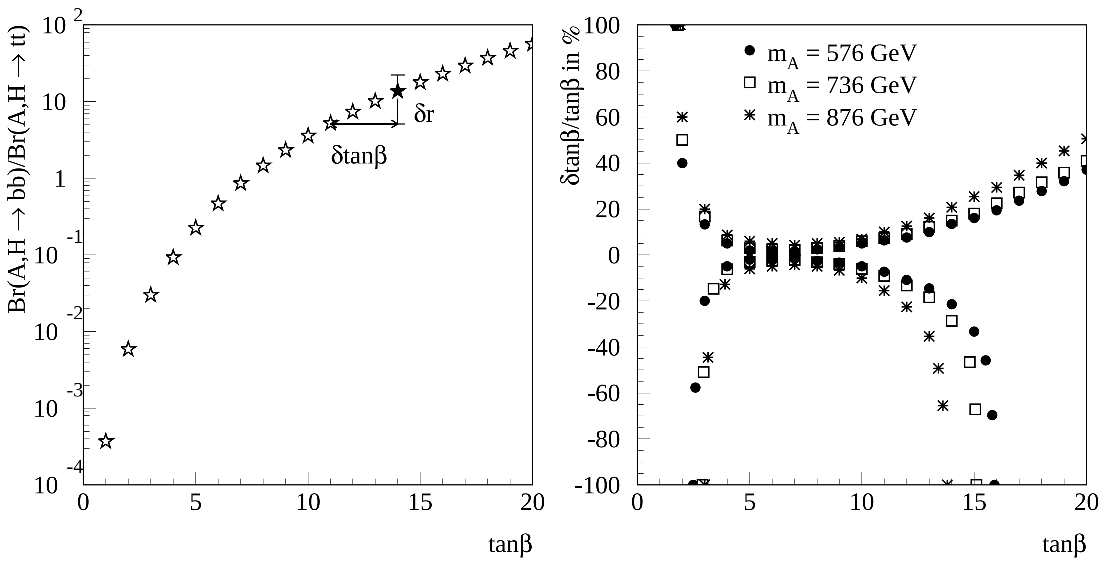
Determination of $tan\beta$

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

The error on r can be written as:

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

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



$\longrightarrow$ $tan\beta$ 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 χ^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.