Extensions of the scalar sector at CLIC

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Outline

CLIC

Compact **Li**near **C**ollider

CLIC will start with an energy of 350/380 GeV. Upgradeable to 1.5 and 3 TeV.

- Deviations from the Standard Model (SM) will be evidence of new physics.
- Expected $\mathcal{O}(1\%)$ precision in fermion, and vector boson couplings with Higgs.
- Accurate measurement of trilinear and quartic Higgs couplings.

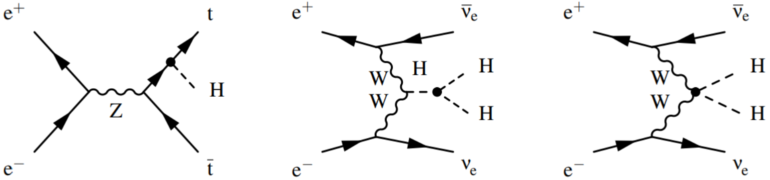

Figure: Main processes containing a top-quark Yukawa coupling $g_{t\bar{t}H}$, trilinear self-coupling g_{HHH}, and g_{WWHH}.

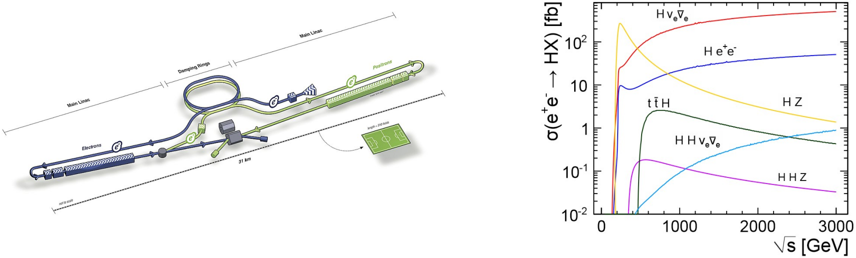

Figure: A general linear collider schematics (left) and the expected main Higgs processes (right).

Motivation

While the Standard Model (SM) predicts several phenomena with an exceptional level of accuracy, for instance:

- The anomalous magnetic moment of the electron, muon.
- Several low energy processes with an incredible level of accuracy. E.g. results from the LEP experiment.

It, nevertheless, fails to account for:

- **Gravity**.
- **Dark Matter**. Several observational evidence: Galaxy rotation curves, Gravitational lensing, Cosmic microwave background, etc.
- **More CP-violation**. CP-violation from weak interactions is not enough to fulfil Sakharov's conditions.

The models under scrutiny are:

- CxSM - The Standard Model with an additional complex singlet.
- (C)2HDM - The (Complex) two Higgs doublet model.
- N2HDM - The next-to-minimal two Higgs doublet model.
- NMSSM - Next-to-minimal Super Symmetric model.

All models have at least three neutral scalars, one to be identified with the discovered Higgs.

CxSM

Complex Singlet Extension of the SM

Let $\mathbb{S} = S(x) + iA(x)$ be a complex $SU(2)_L$ singlet. We consider the following extension of the SM given by

$$V = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2} H^\dagger H |\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + a_1 \mathbb{S} + c.c.\right) \quad (1)$$

with a softly-broken $U(1)$ symmetry. If we assume that the new field has a vacuum expectation value (VeV),

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix} \quad \text{and} \quad \mathbb{S} = \frac{1}{\sqrt{2}}\left[v_S + s + i(v_A + a)\right] , \quad (2)$$

then we have three physical states which are a mixture of the original CP-even eigenstates. The rotation matrix can be parametrised as follows:

$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix} , \quad (3)$$

Where $s_i \equiv \sin\alpha_i$ and $c_i \equiv \cos\alpha_i$. Without loss of generality we have:

$$-\frac{\pi}{2} \leq \alpha_i < \frac{\pi}{2} , \quad (4)$$

(C)2HDM

(Complex) Two Higgs Doublet Model

We consider a particular case of the 2-Higgs-Doublet model (2HDM) and its complex version (C2HDM), which softly-breaks a discrete $\mathbb{Z}_2$ symmetry: $\Phi_1 \to \Phi_1$ and $\Phi_2 \to -\Phi_2$

$$\begin{aligned} V = {} & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + h.c.] \end{aligned} \tag{5}$$

- **2HDM** - The model is CP-conserving if the parameters and VEVs are real.
- **C2HDM** - The model is CP-violating if the VEVs are real but m_{12}^2 and λ_5 are complex with different phases.

To avoid flavour changing neutral currents (FCNC) we extend this symmetry to the Yukawa interactions.

The following needs to be fulfilled to keep the vector boson's mass invariant:

$$\sqrt{v_1^2 + v_2^2} \approx 246\text{GeV} \tag{6}$$

N2HDM

Next-to-minimal Two Higgs Doublet Model

This model consists of an additional $SU(2)_L$ doublet and real singlet. In order to avoid FCNC, we generalize the $\mathbb{Z}_2$ softly-broken symmetry of the 2HDM as follows

$$\Phi_1 \to \Phi_1 \,, \quad \Phi_2 \to -\Phi_2 \,, \quad \Phi_S \to \Phi_S \tag{7}$$

We further impose a second discrete symmetry given by

$$\Phi_1 \to \Phi_1 \,, \quad \Phi_2 \to \Phi_2 \,, \quad \Phi_S \to -\Phi_S \tag{8}$$

The most general potential with these symmetries can be written as

$$\begin{aligned} V = {} & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \\ & + \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \end{aligned} \tag{9}$$

After electroweak symmetry breaking (EWSB) we can parametrise the fields as follows

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} , \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix} , \quad \Phi_S = v_S + \rho_S \,, \tag{10}$$

Yukawa interactions

FCNC can be prevented in the (C)2HDM and N2HDM if we extend the aforementioned Z_2 symmetry to the Yukawa interactions, this leads to four types

	u-type	d-type	leptons
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

Table: The four Yukawa types of the $\mathbb{Z}_2$-symmetric 2HDM defined by the Higgs doublet that couples to each kind of fermions.

The Yukawa Lagrangian is defined by

$$\mathcal{L}_Y = -\sum_{i=1}^{3} \frac{m_f}{v} \bar{\psi}_f \left[c^e(H_i ff) + i c^o(H_i ff)\gamma_5 \right] \psi_f H_i \ , \qquad (11)$$

	u-type	d-type	leptons
Type I	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$
Type II	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$
Lepton-specific	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$
Flipped	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$

Table: Components of the Yukawa couplings of the Higgs bosons H_i in the C2HDM.

NMSSM

Next-to-minimal Supersymmetric Model

Any super symmetric model requires the introduction of two doublets. If an additional singlet is present, the μ problem is solved dynamically.
After EWSB, in the CP-conserving NMSSM we have

- Three CP-even and two CP-odd scalars.
- A pair of charged Higgs.

The NMSSM superpotential reads in terms of the hatted superfields

$$\mathcal{W} = \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3 + h_t\widehat{Q}_3\widehat{H}_u\widehat{t}_R^c - h_b\widehat{Q}_3\widehat{H}_d\widehat{b}_R^c - h_\tau\widehat{L}_3\widehat{H}_d\widehat{\tau}_R^c \tag{12}$$

where only the third generation of fermions is present, for simplicity. We expand the fields analogously around their VEVs

$$H_d = \begin{pmatrix} (v_d + h_d + ia_d)/\sqrt{2} \\ h_d^- \end{pmatrix}, \; H_u = \begin{pmatrix} h_u^+ \\ (v_u + h_u + ia_u)/\sqrt{2} \end{pmatrix}, \; S = \frac{v_s + h_s + ia_s}{\sqrt{2}} \tag{13}$$

ScannerS

ScannerS

Program that scans the parameter space of a general (up to dimension 4) scalar potential.

Authors: R. Costa, R. Guedes, M. Mühlleitner, M. O. P. Sampaio, R. Santos, J. Wittbrodt.

Provides interfaces with the following codes:

- **HiggsBounds/Signals**. Uses the experimental cross section limits at LEP, Tevatron and LHC to exclude parameter points at 95% C.L.
- **Superiso**. Calculation of flavour physics observables.
- **SusHi**. Computes the gluon-gluon fusion and b-quark fusion Higgs production cross-section.
- **Hdecay**. Computes the total width for the possible Higgses and their branching ratios.
- **MicrOmegas**. Annihilation cross section into dark matter and relic density.

→ Enables easy model implementation by using a Mathematica package.

→ User analysis can be set in C++ code.

Available at: https://scanners.hepforge.org/

General remarks

→ One of the physical Higgs is to be identified with the discovered one. Fixing its mass to

$$m_{h_{125}} = 125.09 \text{ GeV} \tag{14}$$

→ Other two can have a mass in the range of]30,1000[GeV, except on $m_{h_{125}} \pm 5$ GeV window. This is to avoid interfering signals.

Theoretical constraints:

- Boundedness from below.
- Pertubative unitarity.
- Vacuum is global minimum.

Experimental constraints:

- Maximum 2σ deviation for the S,T and U electroweak precision observables.
- Production and decay rates under the 95% C.L. limits from LEP, Tevatron and LHC.
- For the NMSSM we also impose upper bounds on the relic density and direct detection rates for dark matter.

Parameters Range 1/3

CxSM

The VEVs v_A and v_S are varied in the range

$$1 \text{ GeV} \leq v_A, v_S < 1.5 \text{ TeV} . \tag{15}$$

The mixing angles $\alpha_{1,2,3}$ vary within the limits

$$-\frac{\pi}{2} \leq \alpha_{1,2,3} < \frac{\pi}{2} . \tag{16}$$

(C)2HDM

The angles vary in the range

$$0.5 \leq t_\beta \leq 35 \qquad -\frac{\pi}{2} \leq \alpha_{1,2,3} < \frac{\pi}{2} . \tag{17}$$

The value of $\mathrm{Re}(m_{12}^2)$ is in the range

$$0 \text{ GeV}^2 \leq \mathrm{Re}(m_{12}^2) < 500000 \text{ GeV}^2 . \tag{18}$$

Parameters Range 2/3

(...) The charged Higgs mass is chosen in the range

$$\begin{aligned} 80\ \text{GeV} &\leq m_{H^\pm} < 1\ \text{TeV (Type I)} \\ 580\ \text{GeV} &\leq m_{H^\pm} < 1\ \text{TeV (Type II)} \end{aligned} \tag{19}$$

One of the H_i is restricted to

$$\begin{aligned} 30\ \text{GeV} \leq m_{H_i} < 1\ \text{TeV (Type I)} \\ 500\ \text{GeV} \leq m_{H_i} < 1\ \text{TeV (Type II)} \end{aligned} \tag{20}$$

N2HDM

$$\begin{aligned} -\frac{\pi}{2} \leq \alpha_{1,2,3} < \frac{\pi}{2} \qquad & 0.25 \leq t_\beta \leq 35 \\ 0\ \text{GeV}^2 \leq \text{Re}(m_{12}^2) < 500000\ \text{GeV}^2 \qquad & 1\ \text{GeV} \leq v_S \leq 1.5\ \text{TeV}\ , \\ 30\ \text{GeV} \leq m_{H_i \neq m_{h_{125}}}, m_A \leq 1\ \text{TeV} \qquad & \\ 80\ \text{GeV} \leq m_{H^\pm} < 1\ \text{TeV (type I)} \qquad & 580\ \text{GeV} \leq m_{H^\pm} < 1\ \text{TeV (type II)} \end{aligned} \tag{21}$$

Parameters Range 3/3

NMSSM

For the NMSSM we used `NMSSMTools` for computation of the particle spectrum and its higher order corrections. It also enables a cross-check with:

- Low energy observables.
- HiggsBounds.
- MicrOMEGAs.

Signal strengths are computed from the SM processes multiplied by the effective couplings calculated with `NMSSMTools`.

Parameter range:

	t_β	λ	κ	M_1	M_2	M_3	A_t	A_b	A_τ	$m_{\tilde{Q}_3}$	$m_{\tilde{L}_3}$	A_λ	A_κ	$\mu_{\rm eff}$
				in TeV										
min	1	0	-0.7	0.1	0.2	1.3	-6	-6	-3	0.6	0.6	-2	-2	-5
max	50	0.7	0.7	1	2	7	6	6	3	4	4	2	2	5

Table: Input parameters for the NMSSM scan.

Perturbative unitarity is ensured by enforcing the rough constraint

$$\lambda^2 + \kappa^2 < 0.7^2 \qquad (22)$$

Constraints on the discovered Higgs

The literature presents predictions for the measurement precision of the Higgs couplings to fermions and vector bosons at CLIC. Let us define

$$\kappa_{Hii} = \sqrt{\frac{\Gamma^{BSM}_{Hii}}{\Gamma^{SM}_{Hii}}} \tag{23}$$

Parameter	Relative precision		
	350 GeV 500 fb^{-1}	+1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
κ_{HZZ}	0.43%	0.31%	0.23%
κ_{HWW}	1.5%	0.15%	0.11%
κ_{Hbb}	1.7%	0.33%	0.21%
κ_{Hcc}	3.1%	1.1%	0.75%
κ_{Htt}	–	4.0%	4.0%
$\kappa_{H\tau\tau}$	3.4%	1.3%	<1.3%
$\kappa_{H\mu\mu}$	–	14%	5.5%
κ_{Hgg}	3.6%	0.76%	0.54%
$\kappa_{H\gamma\gamma}$	–	5.6%	< 5.6%

Table: Results of the model-dependent global Higgs fit on the expected precisions of the κ_{Hii}.

→ Benchmark scenarios: **Sc1** (350 GeV), **Sc2** (1.4 TeV) and **Sc3** (3.0 TeV).

Singlet Admixture

In the broken phase, the singlet admixture is given by

$$\Sigma_i^{\text{CxSM}} = (R_{i2})^2 + (R_{i3})^2 \tag{24}$$

The maximum allowed singlet admixture is given by the lower bound on the global signal strength μ which at present is

$$\Sigma^{\text{CxSM}}_{\text{max LHC}} \approx 1 - \mu_{\text{min}} \approx 11\% \,. \tag{25}$$

Let us consider the case where the discovered Higgs is very SM-like when measured at CLIC

$$\kappa_{H_{sm}ii} = 1 \tag{26}$$

Within the most accurate measurements this would lead to

- **CLIC Sc1** - Most accurate → κ_{HZZ}

$$\Sigma^{\text{CxSM}}_{\text{max CLIC@350GeV}} \approx 0.85\% \,, \tag{27}$$

- **CLIC Sc3** - Most accurate → κ_{HWW}

$$\Sigma^{\text{CxSM}}_{\text{max CLIC@3TeV}} \approx 0.22\% \,. \tag{28}$$

C2HDM

Because of CP-violation an additional effect constrains this model: The electric dipole moment (EDM).

→ They affect differently the model depending on which type of Yukawa interactions are considered.

→ Due to Barr-Zee diagrams interference, CP-violation can be present with small EDM.

→ The constraints of EDMs on the C2HDM are available: D. Fontes et al., JHEP 02, 073 (2018), 1711.09419.

We want to see how CLIC complements the information.

Type I

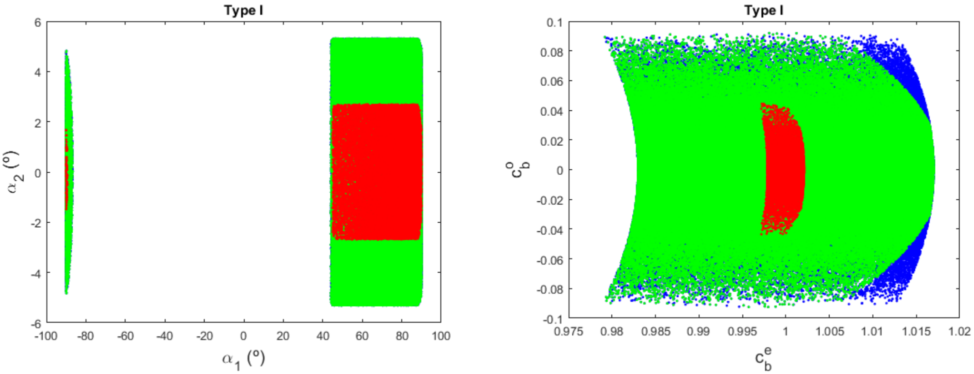

Figure: Mixing angles α_2 vs. α_1 (left) and c_b^o vs. c_b^e (right) for the C2HDM Type I. The blue points are for $Sc1$ but without the constraints from κ_{Hgg} and $\kappa_{H\gamma\gamma}$; the green points are for $Sc1$ including κ_{Hgg} and the red points are for $Sc3$ including κ_{Hgg} and $\kappa_{H\gamma\gamma}$.

C2HDM

Type II

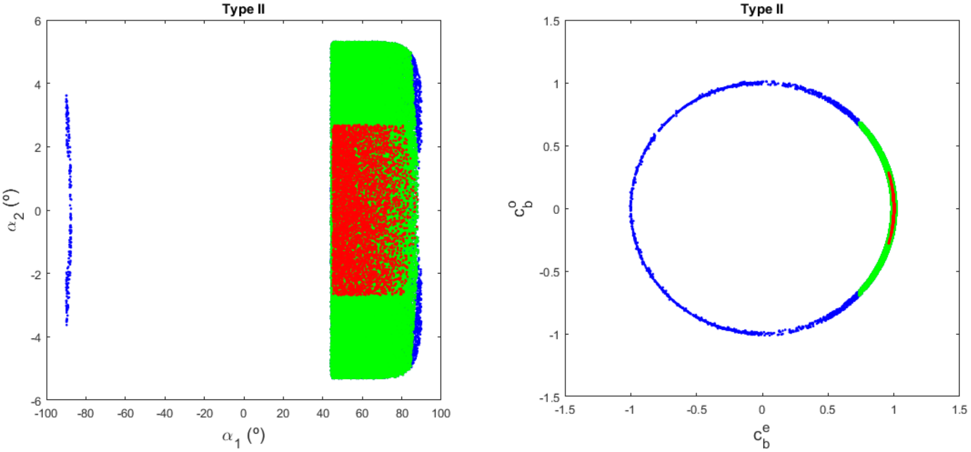

Figure: Mixing angles α_2 vs. α_1 (left) and c_b^o vs. c_b^e (right) for the C2HDM Type II. The blue points are for $Sc1$ but without the constraints from κ_{Hgg} and $\kappa_{H\gamma\gamma}$; the green points are for $Sc1$ including κ_{Hgg} and the red points are for $Sc3$ including κ_{Hgg} and $\kappa_{H\gamma\gamma}$.

The wrong-sign limit will be excluded at the end of CLIC with a SM-like Higgs.

2HDM and N2HDM

Prediction for both models are very similar. Since there's an additional singlet, the discovered Higgs couplings to bosons and fermions is scaled from the 2HDM by

$$g_{hVV}^{N2HDM} = \sin\alpha_2 \, g_{hVV}^{2HDM} \tag{29}$$

→ Translates to an additional degree of freedom.

Type I

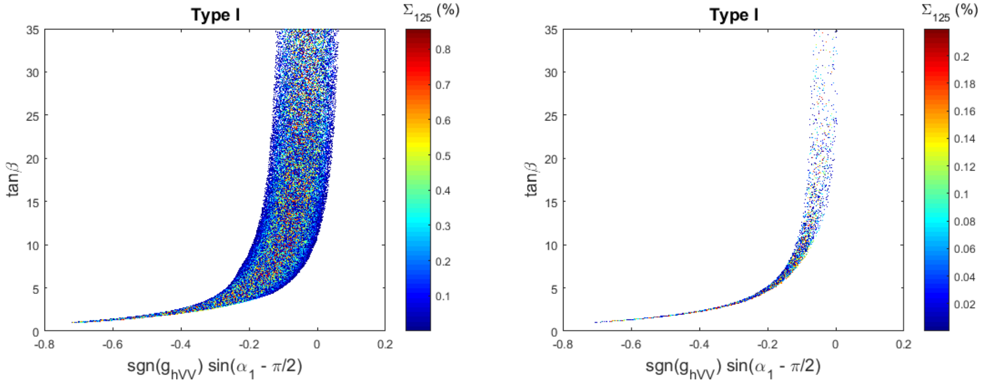

Figure: tan β as a function of $\sin(\alpha_1 - \frac{\pi}{2})$ for Type I in *Sc*1 (left) and *Sc*3 (right). The factor $-\frac{\pi}{2}$ is due to a different definition of the rotation angles relative to the 2HDM. Also shown in the colour code is the amount of singlet admixture present in h_{125}.

In the N2HDM the admixture is given by $\Sigma_{125} = (R_{i3})^2$

2HDM and N2HDM

Type II

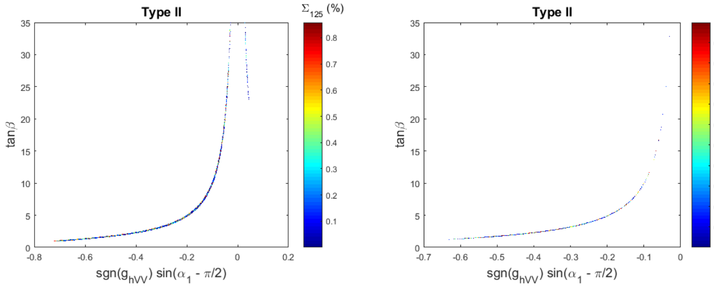

Figure: Same for type II.

Here we also have the wrong-sign limit excluded at the end of CLIC with a SM-like Higgs.

We have the following relation in the extended models studied

$$\kappa^2_{ZZ,WW} + \Psi + \Sigma \leq 1 \tag{30}$$

where $\Psi_{C2HDM} = (R_{i3})^2$. Since the unitarity relation holds in all our models it is independent of both model and Yukawa type, the bounds are then

- $Sc1$: $\Sigma, \Psi < 0.85\%$ from κ_{HZZ}
- $Sc2$: $\Sigma, \Psi < 0.30\%$ from κ_{HWW}
- $Sc3$: $\Sigma, \Psi < 0.22\%$ from κ_{HWW}

SM-like Higgs signal strengths

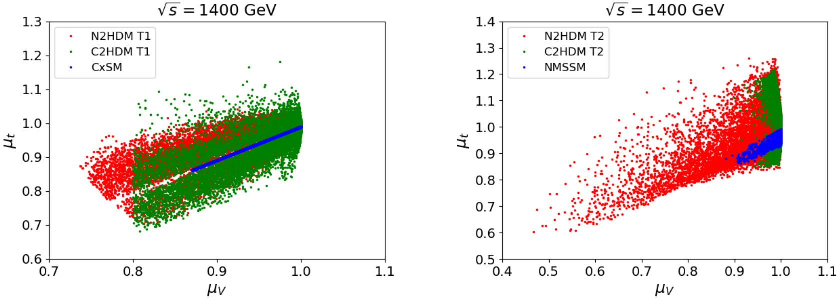

Figure: $\mu_t = \sigma^{BSM}_{\bar{t}th}/\sigma^{SM}_{\bar{t}th}$ as a function of $\mu_V = \sigma^{BSM}_{VVh}/\sigma^{SM}_{VVh} = \left(g^{BSM}_{VVh}/g^{SM}_{VVh}\right)^2$, where $V = W, Z$.

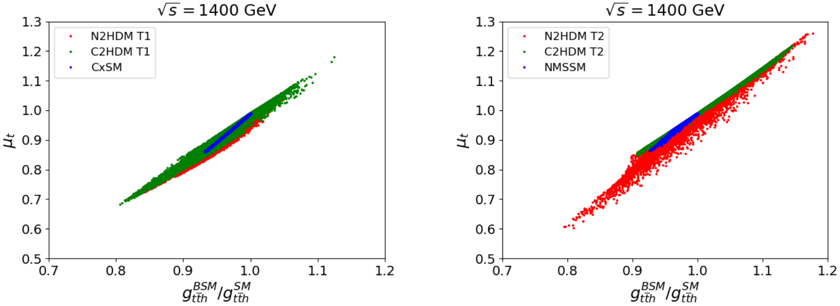

Figure: $\mu_t = \sigma^{BSM}_{\bar{t}th}/\sigma^{SM}_{\bar{t}th}$ as a function of $g^{BSM}_{\bar{t}th}/g^{SM}_{\bar{t}th}$.

Production rates for non-SM-like Higgs

Let us compare the main production processes for the other neutral Higgses. We denote by $H_\downarrow$ the lighter and by $H_\uparrow$ the heavier of the two neutral non-h_{125} Higgs bosons.

- Signal rates are obtained by multiplying the production cross section with the corresponding branching ratio obtained from `sHDECAY`, `C2HDM_HDECAY`, `N2HDECAY` and `NMSSMCALC`.
- Particles with different CP-number are treated on equal footing.
- Main production modes: Higgs Strahlung ($e^+e^- \to ZH$) and WW-fusion ($e^+e^- \to \nu\bar{\nu}H$)

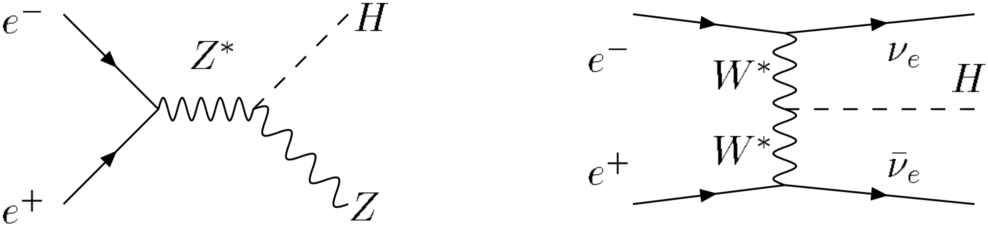

Figure: Main Higgs production modes at a linear collider.

350 GeV CLIC

→ Comparison between non-SM-like Higgses.

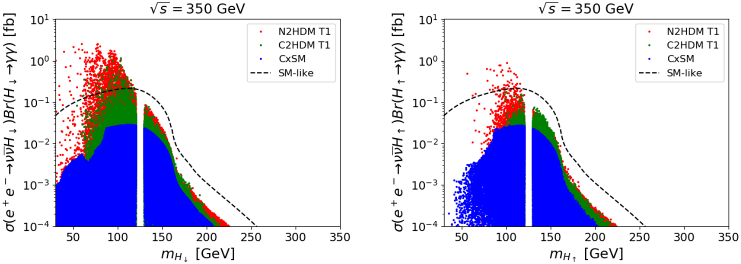

Figure: Total rate for $e^+e^- \to \nu\bar{\nu}H_i \to \nu\bar{\nu}\gamma\gamma$ as a function of the Higgs boson mass for $\sqrt{s} = 350$ GeV.

→ Comparison between models of different types.

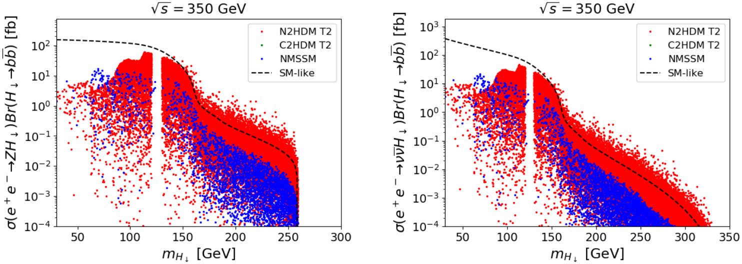

Figure: Total rate for $e^+e^- \to ZH_\downarrow \to Zb\bar{b}$ (left) and for $e^+e^- \to \nu\bar{\nu}H_\downarrow \to \nu\bar{\nu}b\bar{b}$ (right) as a function of $m_{H_\downarrow}$ for $\sqrt{s} = 350$ GeV.

1400 GeV CLIC

→ **WW-fusion becomes dominant with higher energies.**

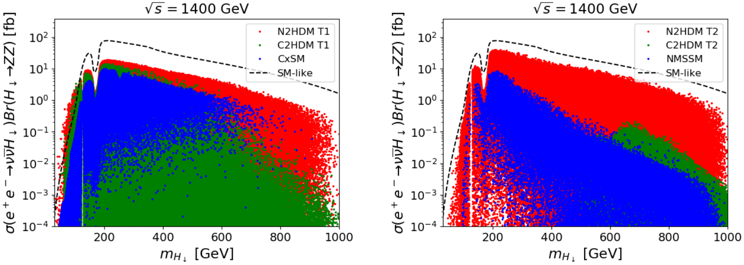

Figure: Total rate for $e^+e^- \to \nu\bar{\nu}H_\downarrow \to \nu\bar{\nu}ZZ$ as a function of the lighter Higgs boson mass for $\sqrt{s} = 1.4$ TeV.

→ **Effect of Sc1 on the signal rates**.

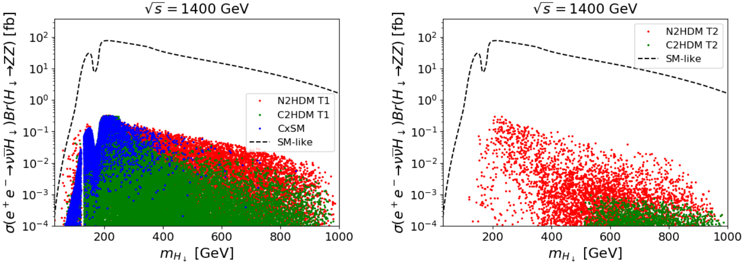

Figure: Same as figure above after imposing the final results for the 350 GeV run.

Associated Production

Another mode is the associated production of Higgs with top-quarks.

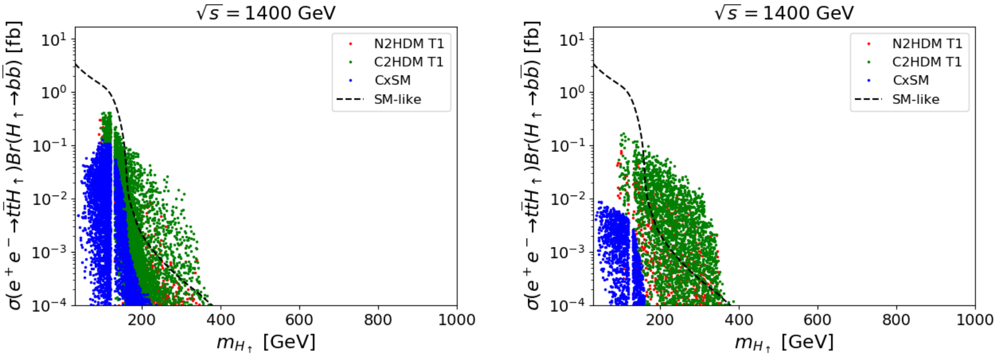

Figure: Total rates for $e^+e^- \to t\bar{t}H_\uparrow \to t\bar{t}b\bar{b}$ for the type 1 N2HDM and C2HDM and CxSM. No 350 GeV CLIC constraints (left) and with constraints (right).

- The CxSM is the most constrained due to the fewer degrees of freedom.
- Associated production rivals the other production modes when considering the 350 GeV CLIC constraints.

Conclusions

We have studies several BSM scalar extensions, CxSM, (C)2HDM, N2HDM (Type I and II) and the NMSSM at the future Compact Linear Collider, using the expected benchmarks for energies of 350, 1400, 3000 GeV.

- These benchmarks were used to constrain the 125 GeV Higgs to be very SM-like, and see the possible deviations from CP-even and doublet-like structure still available.
- We show that CLIC results constrain further the singlet admixture and CP-odd component.

On the second part we studied the possibility of finding and studying additional Higgs bosons at CLIC through Higgstrahlung, WW-fusion and associated production.

- Checking if the models can be disentangled with the discovery of a new particle in the first stage.
- Verified the remaining parameter space, in case of no new physics in the first run.

Thank you!

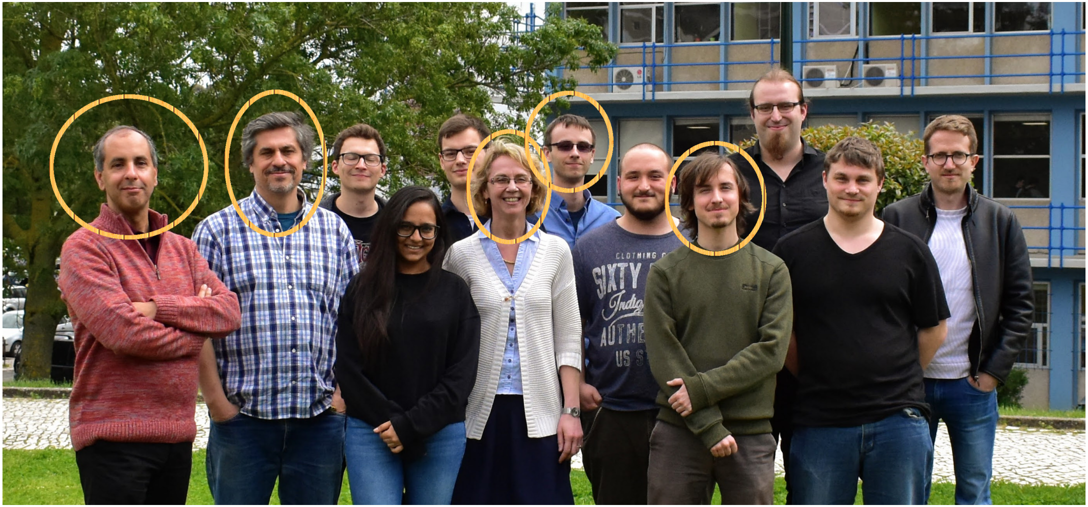

Figure: Left to right: P. Ferreira, R. Santos, M. Mühlleitner, J. Wittbrodt, D. Azevedo.