Models with extended Higgs sectors at future e^+e^- colliders

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Outline

Compact Linear Collider (CLIC)

CLIC

Compact Linear Collider

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.

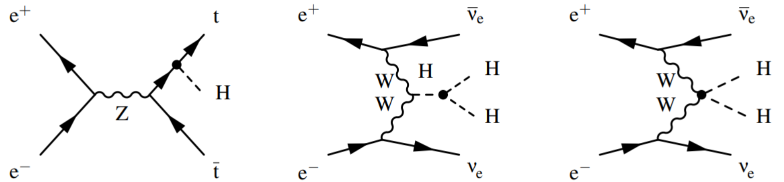


Figure: Main processes containing a top-quark Yukawa coupling $g_{t\bar{t}H}$, trilinear self-coupling g_{HHH}, and g_{WWHH}.

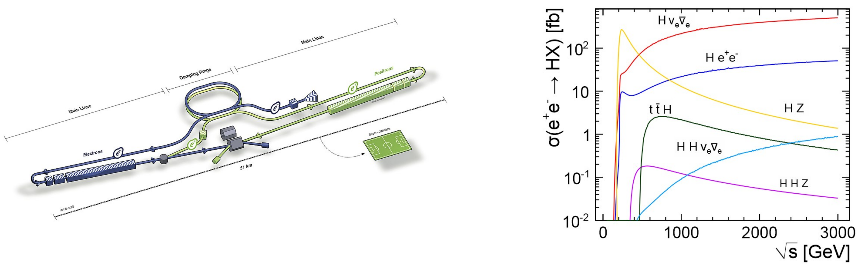


Figure: A general linear collider schematics (left) and the expected main Higgs processes (right).

Scalar extensions

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

First introduced as a scalar dark matter (DM) model.

Let $\mathbb{S} = S(x) + iA(x)$ be a complex $SU(2)_L$ singlet.
We consider the following addition to the of the SM scalar potential

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

$\rightarrow$ softly-broken $U(1)$ symmetry.
The new field is allowed a vacuum expectation value (VEV)

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

This is the broken phase of the CxSM with three physical mixed states h_1, h_2, h_3, one identified as the 125 GeV Higgs.

(C)2HDM

(Complex) Two Higgs Doublet Model

We consider a particular case of the 2-Higgs-Doublet model (2HDM) and its complex version (C2HDM).
Both obey a discrete $\mathbb{Z}_2$ symmetry to eliminate tree-level flavour changing neutral currents (FCNC).

$$\Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2 \tag{3}$$

The scalar potential reads

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

- **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.

The neutral VEVs of both doublets are set to

$$\sqrt{v_1^2 + v_2^2} \approx 246\text{GeV} \tag{5}$$

to keep the gauge bosons mass to their experimental value.
$\rightarrow$ **Three mixed neutral scalars and a charged one.**

N2HDM

Next-to-minimal Two Higgs Doublet Model

This model consists of an additional $SU(2)_L$ doublet and real singlet.
In relation to the 2HDM, we impose a second $\mathbb{Z}_2$ symmetry given by

$$\Phi_S \to -\Phi_S \tag{6}$$

The scalar potential reads

$$\begin{aligned} V = {} & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \\ & + \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \end{aligned} \tag{7}$$

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

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \quad \Phi_S = v_S + \rho_S \,, \tag{8}$$

Additional remarks

For the previous models the the rotation matrix can be parametrised as follows:

$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix} \tag{9}$$

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

$$-\frac{\pi}{2} \leq \alpha_i < \frac{\pi}{2}\,, \tag{10}$$

The Yukawa interactions can be parametrized as

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

	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

The $\mathbb{Z}_2$ symmetry preventing FCNCs reduces the possibilities of the doublet-fermions Yukawa interactions.

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

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

$\rightarrow$ **Equivalent to a type II 2HDM.**

Parameter Scan

ScannerS

ScannerS

Parameter space scanner of a general (up to dimension 4) scalar potential. [R. Costa, R. Guedes, M. Mühlleitner, M. O. P. Sampaio, R. Santos, J. Wittbrodt. JHEP 1703 (2017) 094.]

Provides interfaces with the following HEP codes: HiggsBounds/Signals, SuperISO, SusHi, HDECAY and MicrOMEGAS.
→ Enables easy model implementation through Mathematica notebooks.
→ User analysis can be easily set in premade C++ templates.
→ I am responsible for the maintainance and upgrade of the code. Updated HB5/HS2 interface and implementation of new scalar and vector DM models.
Available at: https://scanners.hepforge.org/

Going through a major core upgrade, with faster tools for numerical scans, better user interface, implementation of electric dipole moments (EDM) contraints, among others.

General remarks

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

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

$\rightarrow$ Other two can have a mass in the range of]30,1000[GeV, except on $m_{h_{125}} \pm 5$ GeV window. No degenerancy.

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.

Constraint on the SM-like Higgs

Consider the *worst* scenario: that measurement of the SM-like Higgs boson couplings does not deviate from SM predictions. Given the precision what is the parameter space left for these models?

$$\kappa_{Hii} = \sqrt{\frac{\Gamma^{BSM}_{Hii}}{\Gamma^{SM}_{Hii}}} = 1 \tag{15}$$

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}.
[CLICdp, E. Sicking, Nucl. Part. Phys. Proc. 273-275, 801 (2016)]

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

Main results

SM-like Higgs

In the broken phase, the singlet admixture is given by

$$\Sigma_i^{\text{CxSM}} = (R_{i2})^2 + (R_{i3})^2 \tag{16}$$

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

$$\Sigma^{\text{CxSM}}_{\text{max LHC}} \approx 1 - \mu_{\text{min}} \approx 11\% \, . \tag{17}$$

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

$$\kappa_{H_{sm}ii} = 1 \tag{18}$$

Within the most accurate measurements this would lead to

- **CLIC Sc1** - Most accurate $\rightarrow \kappa_{HZZ}$

$$\Sigma^{\text{CxSM}}_{\text{max CLIC@350GeV}} \approx 0.85\% \, , \tag{19}$$

- **CLIC Sc3** - Most accurate $\rightarrow \kappa_{HWW}$

$$\Sigma^{\text{CxSM}}_{\text{max CLIC@3TeV}} \approx 0.22\% \, . \tag{20}$$

Main results

SM-like Higgs

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.

$$\mathcal{L}_Y = -\sum_{i=1}^{3} \frac{m_f}{v} \bar{\psi}_f \left[c^e(H_i ff) + i c^o(H_i ff)\gamma_5 \right] \psi_f H_i \ , \tag{21}$$

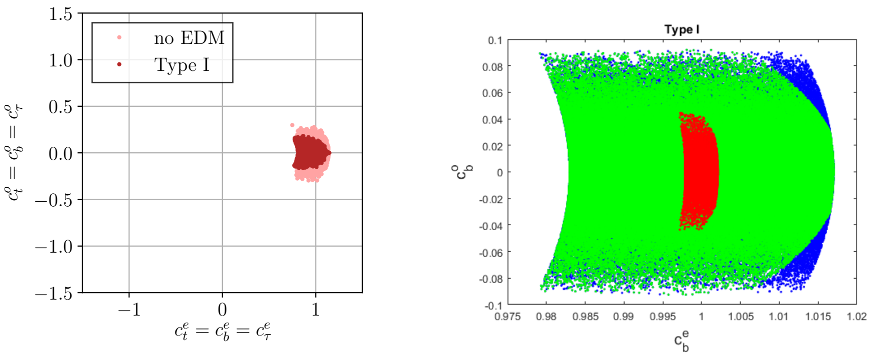
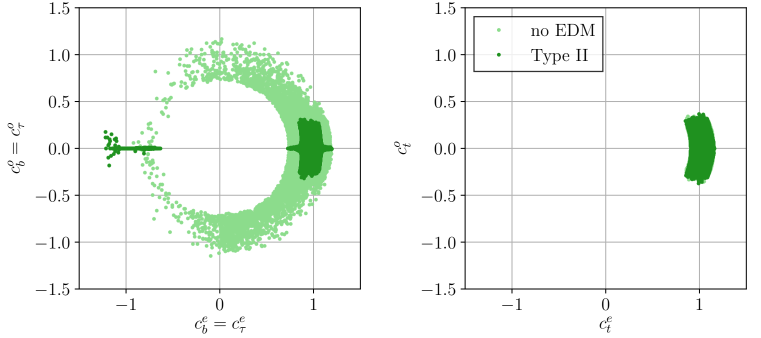
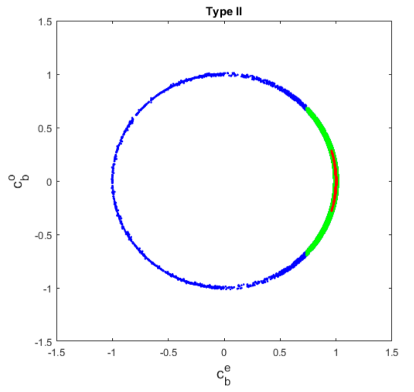


Figure: CP-odd (c_b^o) vs. CP-even (c_b^e) (right) Yukawa couplings for the C2HDM Type I. Current EDM bounds [D. Fontes et al., JHEP 02, 073 (2018)] (left) and CLIC expected bounds (right). The blue points are for $Sc1$ but without the constraints from κ_{Hgg} and $\kappa_{H\gamma\gamma}$; the green points are for $Sc1$ including κ_{Hgg} and the red points are for $Sc3$ including κ_{Hgg} and $\kappa_{H\gamma\gamma}$.

Main results
SM-like Higgs

Type II

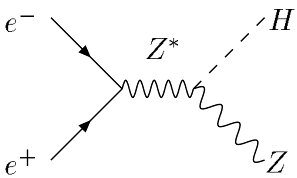


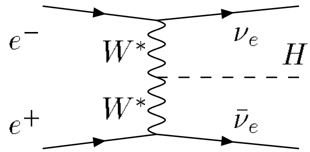


Main results

non SM-like Higgs

Main production modes at lower energies:





WW-fusion becomes main production with higher energies.

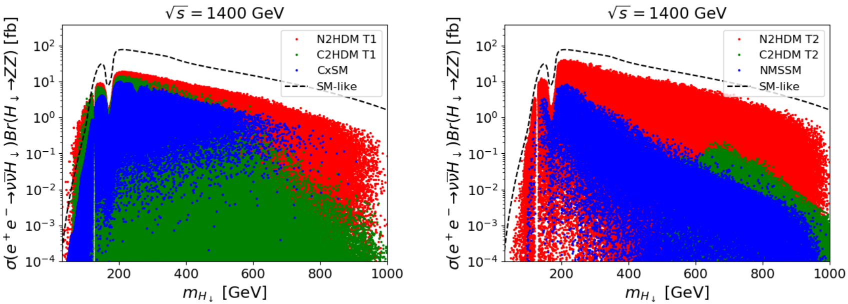
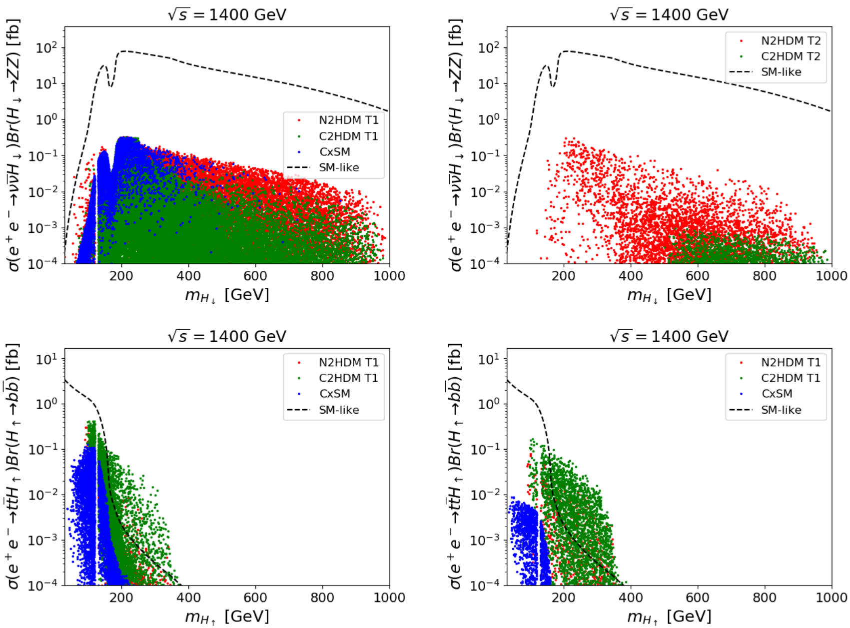


Figure: Total rate for $e^+e^- \to \nu\bar{\nu}H_\downarrow \to \nu\bar{\nu}ZZ$ as a function of the lighter Higgs boson mass for $\sqrt{s} = 1.4$ TeV.

Main results

non SM-like Higgs

→ Effect of Sc1 on the signal rates:



- The CxSM is the most constrained due to the fewer degrees of freedom.
- Associated production rivals the other production modes when considering Sc1.

Conclusions

Published: Phys. Rev. D 99, 055013 (2019).

We have studied 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.
- NMSSM was gone, maybe new particle to be discovered?

Thank you!

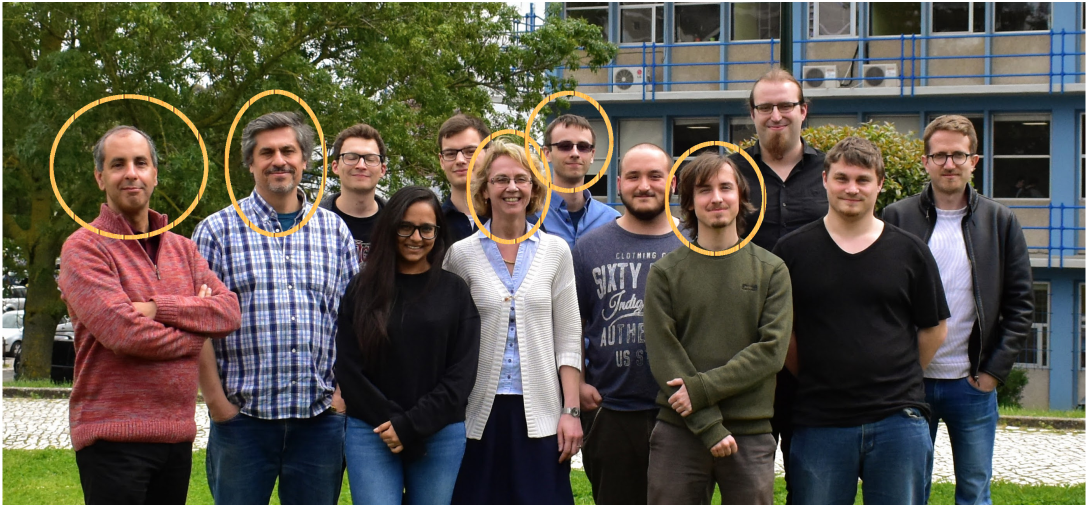


Figure: Left to right: P. Ferreira, R. Santos, M. Mühlleitner, J. Wittbrodt, D. Azevedo.

Backup

Parameters Range 1/3

CxSM

The VEVs v_A and v_S are varied in the range

$$1 \text{ GeV } \leq v_A, v_S < 1.5 \text{ TeV} . \tag{22}$$

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

$$-\frac{\pi}{2} \leq \alpha_{1,2,3} < \frac{\pi}{2} . \tag{23}$$

(C)2HDM

The angles vary in the range

$$0.5 \leq t_\beta \leq 35 \qquad -\frac{\pi}{2} \leq \alpha_{1,2,3} < \frac{\pi}{2} . \tag{24}$$

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

$$0 \text{ GeV}^2 \leq \text{Re}(m_{12}^2) < 500000 \text{ GeV}^2 . \tag{25}$$

Parameters Range 2/3

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

$$\begin{aligned} 80\text{ GeV} &\leq m_{H^\pm} < 1\text{ TeV (Type I)} \\ 580\text{ GeV} &\leq m_{H^\pm} < 1\text{ TeV (Type II)} \end{aligned} \tag{26}$$

One of the H_i is restricted to

$$\begin{aligned} 30\text{ GeV} \leq m_{H_i} < 1\text{ TeV (Type I)} \\ 500\text{ GeV} \leq m_{H_i} < 1\text{ TeV (Type II)} \end{aligned} \tag{27}$$

N2HDM

$$\begin{aligned} -\frac{\pi}{2} \leq \alpha_{1,2,3} < \frac{\pi}{2} \qquad & 0.25 \leq t_\beta \leq 35 \\ 0\text{ GeV}^2 \leq \text{Re}(m_{12}^2) < 500000\text{ GeV}^2 \qquad & 1\text{ GeV} \leq v_S \leq 1.5\text{ TeV}\,, \\ 30\text{ GeV} \leq m_{H_i \neq m_{h_{125}}}, m_A \leq 1\text{ TeV} \qquad & \\ 80\text{ GeV} \leq m_{H^\pm} < 1\text{ TeV (type I)} \qquad & 580\text{ GeV} \leq m_{H^\pm} < 1\text{ TeV (type II)} \end{aligned} \tag{28}$$

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 in TeV	$m_{\tilde{Q}_3}$	$m_{\tilde{L}_3}$	A_λ	A_κ	μ_{eff}
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

$$\lambda^2 + \kappa^2 < 0.7^2 \tag{29}$$