Extended Scalar Sectors at CLIC

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Phys. Rev. D 99, 055013 (2019)

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Scalars 2019
Warsaw

Karlsruher Institut für Technologie

Supported by: NSC, Poland, HARMONIA UMO-2015/18/M/ST2/00518

Overview

Introduction

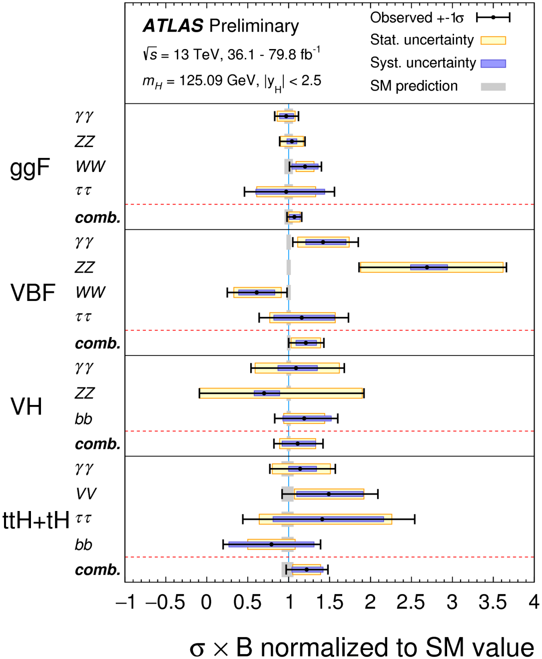
Standard Model...

→ **Scalar particle discovered in 2012 with mass of ∼ 125 GeV at the Large Hadron Collider (LHC)**.
ATLAS, Phys.Lett. B716 (2012), and CMS, Phys. Lett. B 716 (2012).

The Standard Model (SM) is complete. There is no experimental result that strongly deviates from the predictions. Some mentionable exceptions:

- Muon's anomalous magnetic moment.
- B meson decay rate which *seem* incompatible with the SM prediction.

ATLAS-CONF-2018-031



...and Beyond

Still we know it cannot be the whole story.

- **Dark Matter:** Several indirect evidence: Galaxy rotation curves, Gravitational lensing, Cosmic microwave background, etc.
- **Enough CP-violation:** to support Sakharov's condition for baryogenesis.

Extended scalar sectors tackle these by introducing new Electroweak (EW) objects to the scalar sector!

- 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. One additional singlet.
- NMSSM - Next-to-minimal Super Symmetric model.

Extended Scalar Sectors

CxSM

Complex Singlet Extension of the SM

SM + Complex Singlet

- First introduced as DM candidate. Phys. Lett. 161B (1985), Phys. Rev. D50 (1994).
- Produce strong first order phase-transitions JHEP 0708 (2007), Phys. Rev. D86 (2012),...

Let $\mathbb{S} = S(x) + iA(x)$ be a complex a EW singlet. The scalar potential reads

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

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

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

$\rightarrow$ All states mix, we have **three physical scalars** (one to be identified as the Higgs)

(C)2HDM

(Complex) Two Higgs Doublet Model

SM + Doublet

- One of the first BSM models with spontaneous CP-violation Phys. Rev. D 8 (1973) 1226
- Alternatively, can also provide a DM candidate.

→ Consider a scalar sector with two EW doublets Φ_1 and Φ_2.

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + h.c.] \tag{3}$$

with real VEVs

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix} \tag{4}$$

- No flavour changing neutral currents (FCNC) due to $\mathbb{Z}_2$ symmetry $\Phi_2 \to -\Phi_2$.
- Complex m_{12}^2 and λ_5 (with different phases) $\Longrightarrow$ **CP-violation** (C2HDM).
- We end up with three physical neutral scalars (one to be identified as the Higgs).
- ...and a pair of charged scalar!

N2HDM

Next-to-minimal Two Higgs Doublet Model

SM + Doublet + Real singlet

- Minimal scalar extension to provide a DM candidate and CP-violation. JHEP 1811 (2018)

The potential reads

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \tag{5}$$
$$+ \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2$$

with real VEVS

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \quad \Phi_S = v_S + \rho_S\,, \tag{6}$$

- Same FCNC suppressing $\mathbb{Z}_2$ symmetry, $\Phi_2 \to -\Phi_2$.
- Additional $\mathbb{Z}_2$ symmetry, $\Phi_S \to -\Phi_S$.
- Mixing between 3 CP-even + 1 CP-odd state (does not mix) $\Longrightarrow$ **four physical neutral scalars** (CP-eigenstates, one CP-even set to be the Higgs).

Yukawa interactions

→ **FCNCs are completely suppressed at tree-level due to the $\mathbb{Z}_2$ symmetry** (extended to the Yukawa interactions).
Possibilities:

	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

After expanding in the physical basis

$$\mathcal{L}_Y = -\sum_{i=1}^{3} \frac{m_f}{v} \bar{\psi}_f \left[c^e(H_i ff) + i c^o(H_i ff)\gamma_5 \right] \psi_f H_i \ , \tag{7}$$

	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	$\frac{R_{i2}}{s_\beta} - i\frac{R_{i3}}{t_\beta}\gamma_5$	$\frac{R_{i1}}{c_\beta} - it_\beta R_{i3}\gamma_5$	$\frac{R_{i2}}{s_\beta} + i\frac{R_{i3}}{t_\beta}\gamma_5$

NMSSM
Next-to-minimal Supersymmetric Model

$\rightarrow$ Supersymmetry requires at least two doublets. If an additional real singlet is present, the μ problem is solved dynamically. (through a non-trivial vacuum)
After EW phase transition, 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

$$\mathcal{W} = \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3 + h_t\widehat{Q}_3\widehat{H}_u\widehat{t}_R^c - h_b\widehat{Q}_3\widehat{H}_d\widehat{b}_R^c - h_\tau\widehat{L}_3\widehat{H}_d\widehat{\tau}_R^c + \dots \quad (8)$$

We consider real VEVs

$$H_d = \begin{pmatrix} (v_d + h_d + ia_d)/\sqrt{2} \\ h_d^- \end{pmatrix}, \; H_u = \begin{pmatrix} h_u^+ \\ (v_u + h_u + ia_u)/\sqrt{2} \end{pmatrix}, \; S = \frac{v_s + h_s + ia_s}{\sqrt{2}} \quad (9)$$

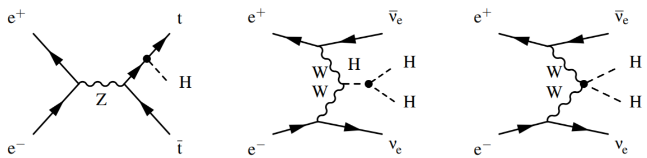
Results

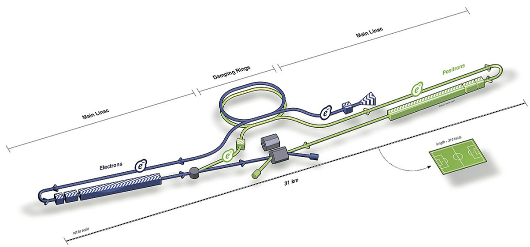
Compact Linear Collider (CLIC)

general for other colliders

→Future linear colliders will start at 250/350/380 GeV. CLIC will be upgradeable to 1.5 and 3 TeV.

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





→ **We scan the parameter space and check it against CLIC expectations.**

CLIC expectations (The pessimistic slide)

Consider the *worst* scenario: the 125 GeV Higgs is SM-like. Given the precision what is the parameter space left for these models?

$$\kappa_{Hii} = \sqrt{\frac{\Gamma^{BSM}_{Hii}}{\Gamma^{SM}_{Hii}}} = 1 \tag{10}$$

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%

[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).

Singlet admixture

Higgs-like scalar

In the broken phase, the singlet admixture is given by

$$\Sigma_i^{\text{CxSM}} = (R_{i2})^2 + (R_{i3})^2 \tag{11}$$

Currently at the LHC, the maximum allowed singlet admixture is given by the lower bound on the global signal strength μ, which is

$$\Sigma_{\text{max LHC}}^{\text{CxSM}} \approx 1 - \mu_{\text{min}} \approx 11\% \; . \tag{12}$$

At CLIC this result would be much more constrained

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

$$\Sigma_{\text{max CLIC@350GeV}}^{\text{CxSM}} \approx 0.85\% \; , \tag{13}$$

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

$$\Sigma_{\text{max CLIC@3TeV}}^{\text{CxSM}} \approx 0.22\% \; . \tag{14}$$

Loop contributions need to be taken into account!

CP-violation
Higgs-like scalar

Case where the lightest scalar is the 125 GeV Higgs.

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

→ Type I.

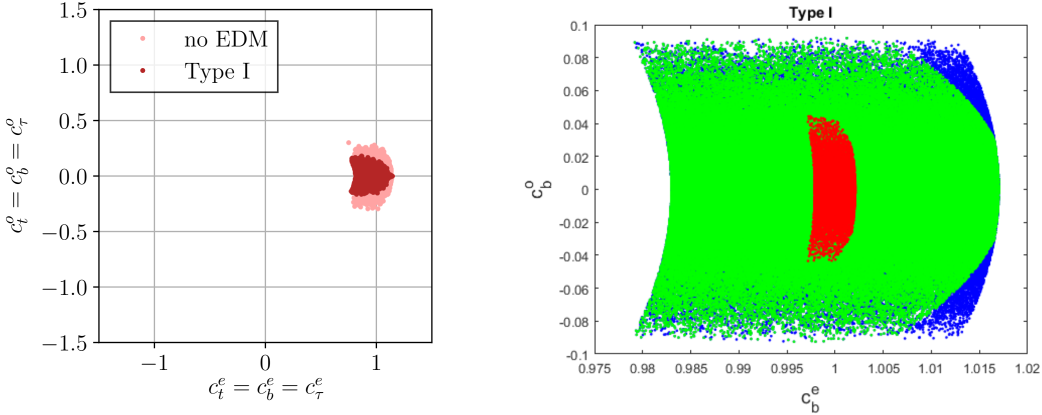


Figure: Current EDM bounds [D. Fontes et al., JHEP 02, 073 (2018)] (left) and CLIC expected bounds (right). The blue points are for $Sc1$ but without the constraints from κ_{Hgg} and $\kappa_{H\gamma\gamma}$; the green points are for $Sc1$ including κ_{Hgg} and the red points are for $Sc3$ including κ_{Hgg} and $\kappa_{H\gamma\gamma}$.

CP-violation
Higgs-like scalar

→ Type II.
→ d-type quarks and leptons.

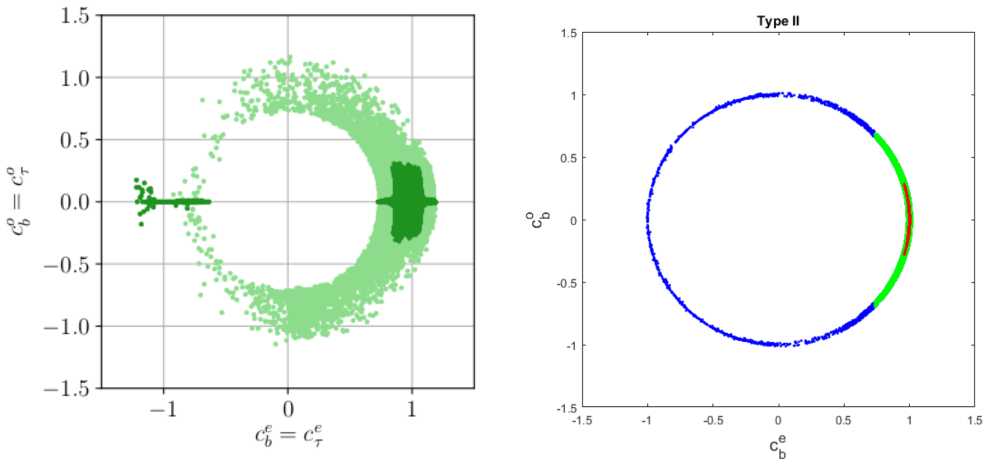
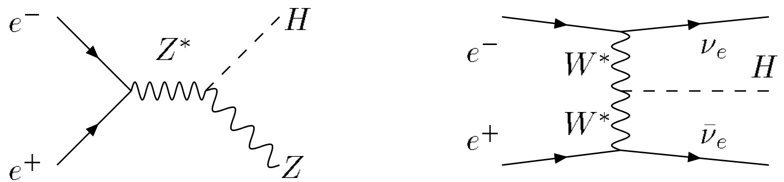


Figure: Current EDM bounds [D. Fontes et al., JHEP 02, 073 (2018)] (left) and CLIC expected bounds (right). The blue points are for $Sc1$ but without the constraints from κ_{Hgg} and $\kappa_{H\gamma\gamma}$; the green points are for $Sc1$ including κ_{Hgg} and the red points are for $Sc3$ including κ_{Hgg} and $\kappa_{H\gamma\gamma}$.

Wrong sign disappears

Production rates
other scalars

Main production modes at lower energies:



WW-fusion becomes main production with higher energies.

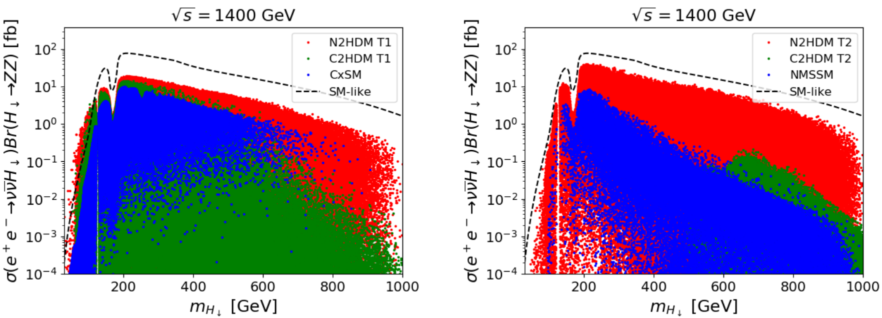
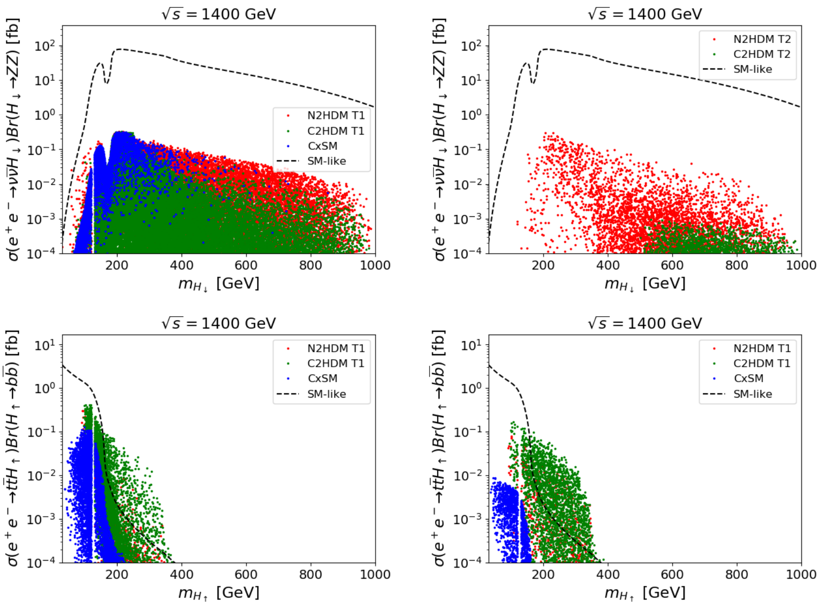


Figure: Total rate for $e^+e^- \to \nu\bar{\nu}H_\downarrow \to \nu\bar{\nu}ZZ$ as a function of the lighter Higgs boson mass for $\sqrt{s} = 1.4$ TeV.

Production rates

other scalars

→ 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

Conclusions

We studied several scalar extensions under CLIC's measurement accuracies, considering the worst scenario.

- SM-like Higgs: CLIC results will severely constrain the possibility of singlet admixture and CP-odd Yukawa component.
- Other scalars: Computed the rates of production within each models, with and without exclusions.
- If we find some particle, some cases may be excluded.

Thank you!

Backup

ScannerS

ScannerS

→ **A parameter space scanner for up-to dim 4 scalar potentials.**

Developed in Lisbon in collaboration with: Aveiro University (Portugal) and Karlsruhe Institute for Technology (Germany). JHEP 1703 (2017) 094,...

- **General potentials:** User-friendly `Mathematica` interface.
- **Theoretical constraints:** Boundedness from below, global minimum, tree-level unitarity.
- **HEP interfaces**: SusHi, HDECAY (and variations), SuperISO, MicrOMEGAS.
- **Collider constraints**: STU parameters, production and decay rates bounds (HiggsBounds 5, HiggsSignals 2).
- **User analysis:** Easily editable `C++` templates.

→ Available at: scanners.hepforge.org

General remarks on the parameter scan

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

$$m_{h_{125}} = 125.09 \text{ GeV} \tag{15}$$

$\rightarrow$ 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

$$1 \text{ GeV } \leq v_A, v_S < 1.5 \text{ TeV} . \tag{16}$$

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

$$-\frac{\pi}{2} \leq \alpha_{1,2,3} < \frac{\pi}{2} . \tag{17}$$

(C)2HDM

The angles vary in the range

$$0.5 \leq t_\beta \leq 35 \qquad -\frac{\pi}{2} \leq \alpha_{1,2,3} < \frac{\pi}{2} . \tag{18}$$

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

$$0 \text{ GeV}^2 \leq \text{Re}(m_{12}^2) < 500000 \text{ GeV}^2 . \tag{19}$$

Parameters Range 2/3

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

$$\begin{aligned} 80 \text{ GeV} &\le m_{H^\pm} < 1 \text{ TeV (Type I)} \\ 580 \text{ GeV} &\le m_{H^\pm} < 1 \text{ TeV (Type II)} \end{aligned} \tag{20}$$

One of the H_i is restricted to

$$\begin{aligned} 30 \text{ GeV} \le m_{H_i} < 1 \text{ TeV (Type I)} \\ 500 \text{ GeV} \le m_{H_i} < 1 \text{ TeV (Type II)} \end{aligned} \tag{21}$$

N2HDM

$$\begin{aligned} -\frac{\pi}{2} \le \alpha_{1,2,3} < \frac{\pi}{2} \qquad & 0.25 \le t_\beta \le 35 \\ 0 \text{ GeV}^2 \le \text{Re}(m_{12}^2) < 500000 \text{ GeV}^2 \qquad & 1 \text{ GeV} \le v_S \le 1.5 \text{ TeV}\,, \\ 30 \text{ GeV} \le m_{H_i \neq m_{h_{125}}}, m_A \le 1 \text{ TeV} \qquad & \\ 80 \text{ GeV} \le m_{H^\pm} < 1 \text{ TeV (type I)} \qquad & 580 \text{ GeV} \le m_{H^\pm} < 1 \text{ TeV (type II)} \end{aligned} \tag{22}$$

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	μ_{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

$$\lambda^2 + \kappa^2 < 0.7^2 \tag{23}$$