(SOME) BSM THEORY*

Rui Santos

ISEL — Instituto Superior de Engenharia de Lisboa
Instituto Politécnico de Lisboa, 1959-007 Lisboa, Portugal
and
Centro de Física Teórica e Computacional, Faculdade de Ciências
Universidade de Lisboa, Campo Grande, Edifício C8, 1749-016 Lisboa, Portugal

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Some of the outstanding issues of the Standard Model (SM) can be solved with an extension of its scalar sector. We discuss SM extensions to tackle matter–antimatter asymmetry, the shape of the Higgs potential, and dark matter. The amount of CP-violation in the SM is not sufficient for baryogenesis and, therefore, new sources of CP-violation are needed. Searches for CP-violation are one of the top priorities of the future LHC runs. Also, the still unknown shape of the Higgs potential can be probed in di-Higgs final states at the LHC. Finally, extensions of the SM can provide dark matter candidates which can be probed at the LHC in events with a large amount of missing energy, together with one or more SM particles.

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1. Introduction

The Standard Model (SM) of particle physics has for many years provided a solid framework for understanding the world surrounding us. There are however some issues the SM cannot handle and an extension of its scalar sector is one possible way out. From the many bottom-up approaches, the inclusion of an enlarged scalar sector is able to provide solutions to some of the outstanding problems of the SM. The matter–antimatter asymmetry of the universe and the existence of dark matter are most likely two of the most prominent problems one needs to address. The new theory still needs to be in agreement with all experimental results in particle physics and with very good precision. Therefore, the addition of new fields has a goal of providing at least one viable DM candidate and new sources of CP-violation that can explain baryogenesis [1]. Searches for CP-violation and DM are among

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the top priorities of the future LHC runs. If these issues are solved with the introduction of an enlarged Higgs potential, its shape can be probed in di-Higgs final states at the LHC.

2. The Higgs potentials and its many extensions

In Fig. 1 we present a list of potentials that introduce the new features that were discussed in the previous section. The SM is shown in magenta and the extensions with singlets and doublets are shown by adding terms in blue, black, and red. The addition of a singlet provides a DM candidate if the corresponding field does not acquire a vacuum expectation value (VEV). The addition of a doublet introduces a new source of CP-violation or a DM candidate but not both. The minimal model with a DM candidate and CP-violation in the scalar sector is the N2HDM with complex parameters, that is, with an extra doublet and an extra singlet. A discussion of the different vacuum phases of the N2HDM can be found in [2]. It is enough to have some of the parameters of the model complex to have CP-violation.

Allows for a decoupling limit

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

Particle (type) spectrum depends on the symmetries imposed on the model, and whether they are spontaneously broken or not.

with fields

$v_2 = 0$, dark matter, IDM

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

$v_S = 0$, singlet dark matter

The one with the larger spectrum is the N2HDM with two charged and four neutral particles.

magenta $\Longrightarrow$ SM

magenta + blue $\Longrightarrow$ RxSM (also CxSM) C stands for "Complex version"

magenta + black $\Longrightarrow$ 2HDM (also C2HDM)

magenta + black + blue + red $\Longrightarrow$ N2HDM

- m^2_{12} and λ_5 real 2HDM
- m^2_{12} and λ_5 complex C2HDM

softly broken Z_2 *2HDM*: $\Phi_1 \to \Phi_1;\ \Phi_2 \to -\Phi_2$

softly broken Z_2 *N2HDM*: $\Phi_1 \to \Phi_1;\ \Phi_2 \to -\Phi_2;\ \Phi_S \to \Phi_S$

exact Z_2' *N2HDM*: $\Phi_1 \to \Phi_1;\ \Phi_2 \to \Phi_2;\ \Phi_S \to -\Phi_S$

Fig. 1. Minimal potentials for the inclusion of new sources of CP-violation and dark matter.

3. CP-violation in extended scalar sectors

The Higgs boson of the SM is a CP-even scalar. The complex phase in the Cabibbo–Kobayashi–Maskawa (CKM) matrix makes this statement only approximately true because CP-violation will appear in Higgs processes via radiative corrections. Searches for CP-violation at the LHC focus mainly on the measurement of 125 GeV Higgs Yukawa couplings. Any deviations from the SM predictions could hint to an extended model with an additional number of fields and possibly also new interactions. If new scalars are found, CP-violation could also be probed in a particular combination of three decays (or more generally, in three interactions).

3.1. CP-violation from P-violation

We start by noting that the current $\bar{f}f$, where f is a fermion, is C-even and P-even, while the current $\bar{f}\gamma_5 f$ is C-even and P-odd. Hence, if the Lagrangian has a Yukawa term of the form of $h_i \bar{f}(a + ib\gamma_5)f$, this is a sign of CP-violation with origin in P-violation, since the complete term in C-invariant provided the scalar would be C-even. Counting experiments at colliders will not distinguish between the scalar and the pseudoscalar couplings, something that can only be achieved with some kind of interference between amplitudes or with the use of particular variables. It is important to note that all Yukawa couplings need to be measured because it is possible to have independent a and b couplings for each SM fermion. In fact, it is even possible to have a Higgs that behaves approximately as a pseudoscalar in its coupling to to τ-leptons or b-quarks, while behaving as a scalar in the couplings to the top-quarks [3, 4]. Presently, only the tau [5, 6] and top couplings [7, 8] are being probed at the LHC.

3.2. CP-violation from C-violation

As discussed in detail in [9, 10], if the theory exhibits CP-violation due to the presence of CP-violating scalar self-interaction terms, then it can be interpreted as C-violation. The way to search for this type of CP-violation at colliders needs at least that one new scalar is found or a loop process shows some sign of CP-violation. In Fig. 2, we show a combination of three decays that signals CP-violation at tree-level (left) and the triangle that looks inside the dark sector of a CP-violating model, with the same combination of decays. The process is also possible if CP-violation is in the visible sector. The anomalous triple gauge boson couplings have a CP-violating term that was measured at the LHC by both ATLAS [11] and CMS [12].

$$h_2 \to h_1 Z \quad CP(h_2) = -\,CP(h_1)$$
$$h_3 \to h_1 Z \quad CP(h_3) = -\,CP(h_1)$$
$$h_3 \to h_2 Z \quad CP(h_3) = -\,CP(h_2)$$

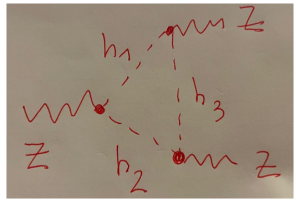


Fig. 2. Left: a combination of three decays that signals CP-violation at tree-level. Right: the triangle that looks inside the dark sector of a CP-violating model, with the same combination of decays. The loop process is also possible if CP-violation is in the visible sector.

In Fig. 3, we present a benchmark point for the complex two-Higgs doublet model (C2HDM) [13, 14]. It is shown that taking all present relevant constraints on the model, a combination of three decays involving three different scalars can still be seen at the next LHC run.

✦ Example C2HDM T1: H_1=SM-like Higgs CP-even, m_{H3} = 267 GeV

m_{H_1} [GeV]	m_{H_2} [GeV]	$m_{H^\pm}$ [GeV]	α_1	α_2	α_3	$\tan\beta$	Re(m_{12}^2) [GeV^2]
125.09	265	236	1.419	0.004	-0.731	5.474	9929

$\sigma^{\rm NLO}_{H_1H_1}$ [fb]	K-factor	$\Gamma^{\rm tot}_{H_1}$ [GeV]	$\Gamma^{\rm tot}_{H_2}$ [GeV]	$\Gamma^{\rm tot}_{H_3}$ [GeV]	$\Gamma^{\rm tot}_{H^\pm}$ [GeV]
387	2.06	4.106×10^{-3}	3.625×10^{-3}	4.880×10^{-3}	0.127
$\lambda_{3H_1}/\lambda_{3H}$	$y^e_{t,H_1}/y_{t,H}$	$\sigma^{\rm NNLO}_{H_1}$ [pb]	$\sigma^{\rm NNLO}_{H_2}$ [pb]	$\sigma^{\rm NNLO}_{H_3}$ [pb]	
0.995	1.005	49.75	0.76	0.84	

$$\begin{aligned}
\sigma(H_2)\times{\rm BR}(H_2\to H_1H_1) &= 191 \text{ fb}\,, & \sigma(H_2)\times{\rm BR}(H_2\to WW) &= 254 \text{ fb}\\
\sigma(H_2)\times{\rm BR}(H_2\to ZZ) &= 109 \text{ fb}\,, & \sigma(H_2)\times{\rm BR}(H_2\to ZH_1) &= 122 \text{ fb}\\
\sigma(H_3)\times{\rm BR}(H_3\to H_1H_1) &= 235 \text{ fb}\,, & \sigma(H_3)\times{\rm BR}(H_3\to WW) &= 315 \text{ fb}\\
\sigma(H_3)\times{\rm BR}(H_3\to ZZ) &= 136 \text{ fb}\,, & \sigma(H_3)\times{\rm BR}(H_3\to ZH_1) &= 76 \text{ fb}\,.
\end{aligned}$$

CP-even CP-odd

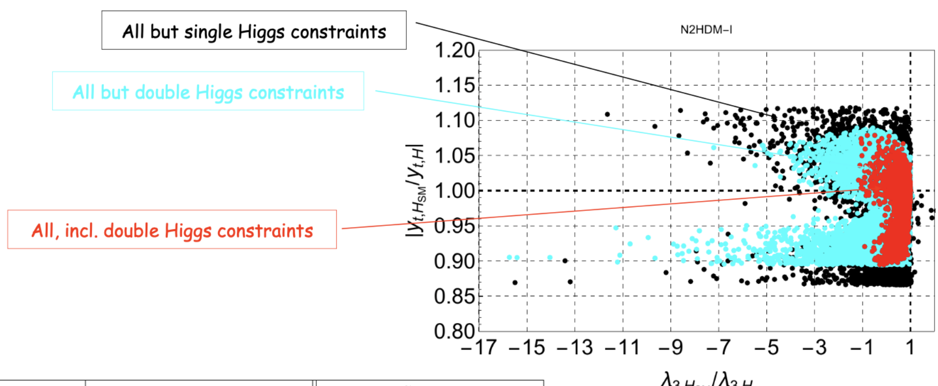
Fig. 3. Benchmark point in the C2HDM for which a combination of three decays could still be seen at the LHC. All relevant available experimental and theoretical constraints were taken into account.

3.3. *CP-violation but dark*

Models with a dark sector with CP-violation were proposed in [15, 16]. In these scenarios, we can probe CP-violation via the loop presented in Fig. 2.

4. Higgs pair production

As previously discussed, the study of final states with two scalars can provide information on the Higgs potential. In this section, we will just discuss two interesting scenarios related to these searches and refer the reader to [13, 14] for a detailed study of di-Higgs and triple-Higgs processes in a number of models. In Fig. 4, we present results for one Yukawa type of the real 2HDM and the complex 2HDM. In this plot, we want to show how the different constraints affect the parameter space of the models. The relevant couplings to distinguish the new model from the SM are the top-Yukawa and the triple-Higgs couplings. It is clear from the figure that double-Higgs results already play an important role in constraining the parameter space of the model. Another interesting point to make is that the triple-Higgs couplings are still compatible with zero for some parameter points.



	R2HDM		C2HDM	
	$y^{\text{R2HDM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{R2HDM}}_{3H_{\text{SM}}}/\lambda_{3H}$	$y^{\text{C2HDM}}_{t,H_{\text{SM}}}/y_{t,H}$	$\lambda^{\text{C2HDM}}_{3H_{\text{SM}}}/\lambda_{3H}$
light I	0.893...1.069	-0.096...1.076	0.898...1.035	-0.035...1.227
medium I	n.a.	n.a.	0.889...1.028	0.251...1.172
heavy I	0.946...1.054	0.481...1.026	0.893...1.019	0.671...1.229
light II	0.951...1.040	0.692...0.999	0.956...1.040	0.096...0.999
medium II	n.a.	n.a.	–	–
heavy II	–	–	–	–

Still compatible with zero

Fig. 4. Allowed regions of the parameter space for one Yukawa type of the real 2HDM and the complex 2HDM. In this plot, we want to show how the different constraints affect the parameter space of the model.

In Fig. 5, we show a point in the parameter space of N2HDM type I, for which the di-Higgs production can be larger than the corresponding single-Higgs process. As explained in the figure, the non-SM-like Higgs is singlet-like and, therefore, there is a suppression of its couplings to SM-like particles. The production processes can also be smaller.

N2HDM-I and NMSSM - 3 SM-like Higgs bosons (H1). NLO rates above 10 fb. Di-Higgs states larger/ comparable with direct production.
Reason: non-SM-like Higgs is singlet-like (suppressed couplings to SM-like particles) and/or is more down- than up-type like (suppressed direct production).

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$
125.09	281.54	441.25	386.98	421.81	1.990
α_1	α_2	α_3	v_s [GeV]	$\mathrm{Re}(m_{12}^2)$ [GeV^2]	
1.153	0.159	0.989	9639	29769	

$$\boxed{\sigma^{\mathrm{NLO}}_{H_1H_2} \times \mathrm{BR}(H_2 \to H_1H_1) \times \mathrm{BR}(H_1 \to b\bar{b})^3 = 509 \cdot 0.37 \cdot 0.60^3 \text{ fb} = 40 \text{ fb}}$$

$$\sigma^{\mathrm{NNLO}}(H_2) \times \mathrm{BR}(H_2 \to H_1H_1) \times \mathrm{BR}(H_1 \to b\bar{b})^2 = 161 \cdot 0.37 \cdot 0.60^2 \text{ fb} = 21 \text{ fb}$$
$$\sigma^{\mathrm{NNLO}}(H_2) \times \mathrm{BR}(H_2 \to WW) = 161 \cdot 0.44 \text{ fb} = 71 \text{ fb}$$

H2 BR to bb tiny.
Non-SM- like H2 has better chances of being discovered in di-Higgs than in single Higgs channels (W bosons still have to decay).

Fig. 5. Point in parameter space for which the di-Higgs production can be larger than the corresponding single Higgs process. The points shown are for the N2HDM type I but there are also points for the NMSSM.

5. Dark matter

Although the existence of dark matter (DM) was first mentioned about 100 years ago [17], we still do not know if it can be a particle from an extended version of the SM. This new field is usually considered to live in a dark sector that connects with the visible world via a portal term in the Lagrangian [18]. In Fig. 6, we present Izma, a portal cat that connects the two worlds.

Fig. 6. Izma, the cat that connects the two worlds. (Picture courtesy of Maria M. Santos.)

The simplest way to extend the SM to include a DM particle is to add a real scalar singlet [19, 20], coupling only to the Higgs doublet. This minimal model, with an unbroken $\mathcal{Z}_2$ symmetry, provides a DM candidate that is already very constrained by experiment and in particular by the DM relic density [21], and the most recent direct detection experiments from LUX-ZEPLIN (LZ) [22], in particular above a DM mass of 125 GeV. The simplest version of the model with just one singlet has a strong bound on the DM mass that has to be above about 4 TeV together with a portal coupling above 1. The addition of more singlets [23] with independent symmetries still leaves the SM interactions unchanged but they open up a new region of light DM masses, of the order of 100 GeV, and large portal couplings. We note that the old region of very heavy particles is still allowed. The scenario in which there is a light DM candidate is a new feature of the two-singlets case.

In Fig. 7, we present the spin-independent cross section of DM-nucleon elastic scattering $S_rN \to S_rN$ $(N = p, n)$ multiplied by the corresponding fraction of DM relic density $\Omega_{S_r}/\Omega_{\mathrm{DM}}$ $(r = 1, 2)$, for both proton (p) and neutron (n) elastic scattering. The points are from the two-singlet extension with two independent $\mathcal{Z}_2$ symmetries and, therefore, two DM candidates that will share the relic density. Also shown are the LZ bounds from 2022 and 2024. The colour bar shows the value of the portal coupling. We call S_1 the light DM particle, while S_2 is the heavy one. It is clear from the figure that although the points are still in the uncertainty band of the latest LZ

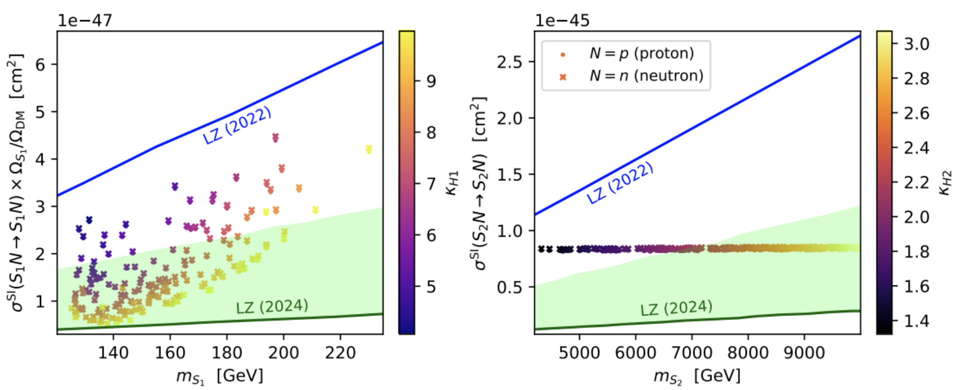


Fig. 7. Spin-independent cross section of DM-nucleon elastic scattering $S_rN \to S_rN$ $(N = p, n)$ multiplied by the corresponding fraction of DM relic density $\Omega_{S_r}/\Omega_{\mathrm{DM}}$ $(r = 1, 2)$, for both proton (p) and neutron (n) elastic scattering. The points are from the two-singlet extension with two independent symmetries. Also shown are the LZ bounds from 2022 and 2024. The colour bar shows the value of the portal coupling.

results, they are bound to be probed by DM direct detection experiments in the near future. The reason for having this new region of light DM is related to the fact that in this case, the fraction of the DM relic density is almost all taken by the heavy DM state. This, in turn, lowers the possible number of events of the light DM, because it has a very low abundance. We have obtained similar results for the scenario with three DM candidates and three independent Z_2 symmetries.

The light DM states also have a large portal coupling. Therefore we could search for these states at the LHC. In Fig. 8, we present the cross section of mono-Higgs production processes $pp \to S_1 S_1 h$ at $\sqrt{s} = 13$ TeV for a set of benchmark points. The red line is the ATLAS (2021) [24] (see also [25]) model-independent experimental upper limit on the cross section. The cross sections for a set of allowed points in the model are shown in the left panel. In the right panel we choose a set of points with a large portal coupling and apply them the cuts corresponding to the ATLAS experimental analysis. Also shown are the colour bar representing either the portal coupling or the DM mass.

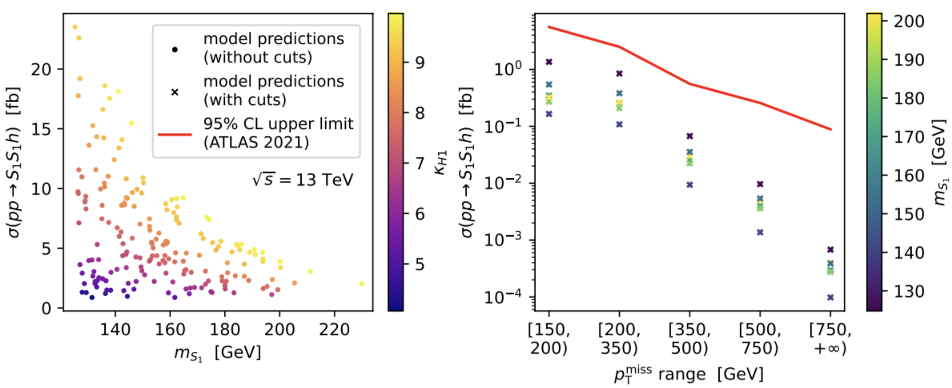


Fig. 8. Cross section of mono-Higgs production processes $pp \to S_1 S_1 h$ at $\sqrt{s} = 13$ TeV for a set of benchmark points. The red line is the ATLAS (2021) model-independent experimental upper limit on the cross section. Left panel: model predictions for the chosen scenarios. Right panel: cross section for six benchmark points with different missing transverse momentum ranges, along with the corresponding ATLAS upper limits. The legend is shared by both panels. The colour bar in the left (right) plot represents the portal coupling (the mass) of the DM particle.

6. Conclusions

Our conclusions are as follows:

— It is now clear why extended scalar sectors may improve your life.

— They provide DM candidates and new sources of CP-violation and are testable at the LHC and future colliders.

— Direct searches for a CP-odd component in the Higgs Yukawa couplings give information that cannot be obtained from the eEDMs. So far, only tau and top couplings were probed directly.

— Combination of data (with eEDMs) has shown to be crucial to probe the entire parameter space of the models, including the searches for new scalars.

— Anomalous coupling experimental information is moving closer to the largest theoretical estimates in simple models with CP-violation in the scalar sector.

— There are numerous BSM Higgs sector extensions with a large variety of resonant and non-resonant Higgs final states.

— Large enhancement through resonant production makes possible tests of CP-violation through Higgs decays together with the Zh_ih_j vertex.

— SM measurements are the starting point to probe BSM models.

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