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Investigating extended scalar sectors at current and future colliders

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In this work, I briefly report on constraints that can be obtained on new physics models that extend the scalar sector of the Standard Model (SM) of particle physics at the LHC. I concentrate on a few simple examples which serve to demonstrate advantages as well as possible drawbacks of current experimental searches, and comment on the discovery prospects of such models at future colliders.

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1. Introduction

During Run-II of the Large Hadron Collider (LHC) at CERN, both the ATLAS and CMS experiments have collected more than $\int \mathscr{L} = 150\,\text{fb}^{-1}$ of data, with results using the full dataset starting to become available [1, 2]. One important quest for the theoretical and experimental community is the understanding of the scalar sector realized by nature. After the discovery of the Higgs boson in 2012 [3, 4], many measurements have confirmed that the discovered boson complies with the properties of the Higgs boson predicted by the SM alone; however, both theoretical and experimental uncertainties still allow for beyond the SM (BSM) models with additional particle content. Understanding the constraints on such models, including detailed investigations of possible discovery channels, is an important task for the experimental and theoretical community.

There are many models that allow for such an extension of the SM scalar sector. In the following, I will focus on three examples that serve to identify strengths as well as possible drawbacks of current and future collider searches. I will first discuss the simplest extension, namely, the introduction of a real scalar which is a singlet under the SM gauge group [5, 6]. This model has a small number of free parameters, and its study can therefore serve to understand the possible interplay of theoretical and experimental constraints within a relatively simple framework. I will then turn to the Inert Doublet Model, a two Higgs doublet model featuring a dark matter (DM) candidate [7–9]. This model renders signatures that are already investigated by the LHC experiments, although currently no dedicated interpretation exists within an experimental analysis. I will briefly comment on possible alterations of the current search strategies which are needed in order to investigate this model at the LHC, as well as discovery prospects at future e^+e^- machines. Finally, I will turn to scalar-to-scalar decays that are currently not investigated by the experimental collaborations, and provide a short overview on interesting new signatures within a specific model, that are produced with feasible rates at the 13 TeV LHC and require new experimental search strategies.

In the analysis of the models discussed here, various tools have been used for the determination of viable regions in the respective models parameter spaces. For the inclusion of signal strength measurements of the 125 GeV scalar as well as null-results for additional scalar searches, we made use of the publicly available tools `HiggsBounds -5.4.0` [10–14] and `HiggsSignals -2.3.0` [15–17].

2. Simple scalar extension of the SM scalar sector

The simplest extension of the SM scalar sector introduces an additional real scalar which is a singlet under the SM gauge groups. After further applying a $\mathbb{Z}_2$ symmetry, the potential of the model is given by

$$V(\Phi, S) = -m^2 \Phi^\dagger \Phi - \mu^2 S^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 S^4 + \lambda_3 \Phi^\dagger \Phi S^2 \tag{2.1}$$

where Φ and S denote the doublet and singlet in the gauge eigenbasis. Both fields acquire a vacuum expectation value (vev); therefore, mass eigenstates are related by a mixing matrix specified by the angle α. One of the scalar masses as well as the doublet vev are fixed from experimental measurements, such that the model has in total 3 undetermined parameters

$$M_{h/H}, \sin\alpha, \tan\beta \equiv \frac{v_\Phi}{v_S},$$

where v denote the respective vevs. All couplings to SM particles are inherited from the doublet in the gauge eigenstate, leading to a universal suppression by $\sin\alpha$ $(\cos\alpha)$ for $h\,(H)$. We here use the convention that $M_H \geq M_h$.

The model is subject to a large number of theoretical and experimental constraints and has been vastly discussed in the literature (see e.g. [18–20] and references therein). For briefness, we here concentrate on the case where $M_h = 125\,\text{GeV}$. In this case, $|\sin\alpha| = 0$ denotes the SM-like decoupling limit. We show a survey of the interplay of all current constraints within this model in figure 1. For large regions of the available parameter space, constraints from the Higgs signal strength measurements as well as direct searches prove to be dominant. For larger masses, however, the use of the W-mass as a precision observable [21] as well as perturbativity of the couplings renders the strongest constraints. Note that the strongest experimental limits mainly stem from searches for $pp \to H \to VV'$, as well as other measurements [22–27].

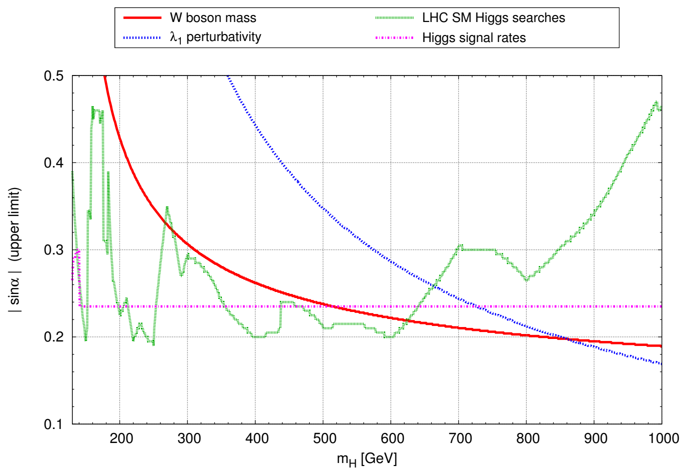

Figure 1: Current constraints on the parameter space of the Higgs singlet extension. Shown are limits from the W-boson mass as a precision observable [21] (solid, red), direct searches as implemented in `HiggsBounds` (green, dashed), limits from signal strength measurements as implemented in `HiggsSignals` (magenta, dashed), as well as limits from perturbativity of λ_1. $\tan\beta$ has been fixed to 0.1. This figure corresponds to an update of results presented in [20].

Another interesting feature is the resonant production of H, followed by a subsequent decay into hh. In fact, this signatures has been vastly investigated by the LHC experiments. We show a comparison of the current experimental search limits [28, 29] with the maximal rate allowed by all theoretical and experimental constraints in figure 2. Note that there is an interesting interplay between limits from perturbativity of the couplings and direct searches for $M_H \gtrsim 400\,\text{GeV}$, leading to a decrease of the maximally allowed mixing angle from the value derived from signal strength measurements, $|\sin\alpha| \lesssim 0.235$, in that mass range.

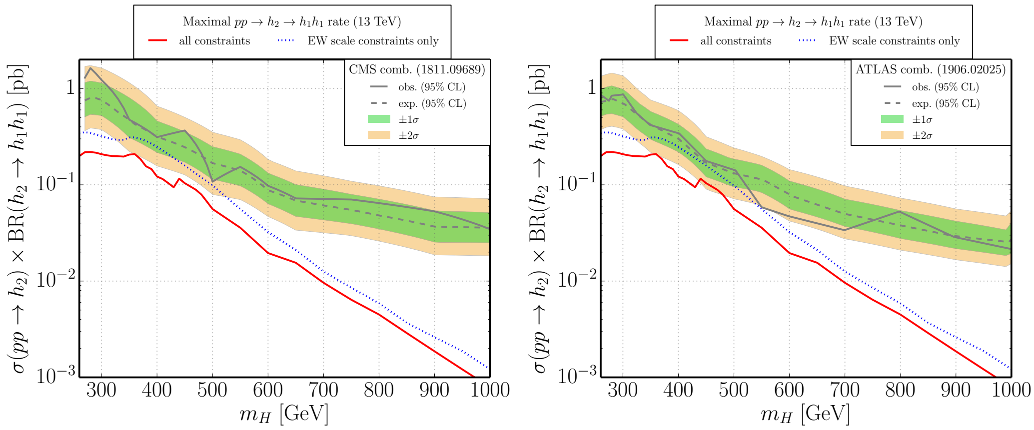

Figure 2: Maximal allowed $pp \to h_2 \to h_1h_1$ signal rate at the 13 TeV LHC in the softly-broken $\mathbb{Z}_2$-symmetric case. Shown are values after applying (red solid) all constraints and (blue dotted) only constraints at the electroweak (EW) scale. For comparison we include the current strongest cross section limit (at 95% CL), obtained from the combination of various CMS $h_2 \to h_1h_1$ searches at 13 TeV with up to 36 fb^{-1} of data [28] *(left)* as well as ATLAS Run II searches with the same integrated luminosity [29] *(right)*. This figure is an update of a result presented in [30].

3. Inert Doublet Model

3.1 Model setup and current constraints

I now turn to a model that, apart from extending the scalar sector of the SM by an additional particle content, also provides a dark matter candidate. The Inert Doublet Model (IDM) [7–9] is a two-Higgs doublet model that comes with an additional exact $\mathbb{Z}_2$ symmetry. This allows to define different transformation properties of the two doublets, which are labelled Φ_S and Φ_D, such that

$$\Phi_D \to -\Phi_D,\ \Phi_S \to \Phi_S,\ \mathrm{SM} \to \mathrm{SM}. \tag{3.1}$$

Following the above transformation properties, only the SM-like doublet Φ_S acquires a vacuum expectation value; therefore, electroweak symmetry breaking proceeds as in the SM. Similarly, the second doublet does not couple to fermions, and therefore all interactions from particle of the second doublet stem from direct scalar-scalar interactions terms in the potential or from the covariant derivative required by gauge symmetry. The model has been vastly explored in the literature (see e.g. [20, 31–34] and references therein, as well as [20, 31, 34–48] for studies of LHC phenomenology). Signatures at colliders always render electroweak gauge bosons and missing transverse energy. Although the model therefore features collider signatures similar to other models which are currently under investigation at the LHC (see e.g. [32] and references therein), the IDM itself has not been explored directly by the LHC experiments.

Due to the above symmetry, Φ_S plays the role of the SM doublet regarding electroweak symmetry breaking; therefore, the scalar excitation of this doublet, which we denote by h, has a mass of $M_h = 125\,\mathrm{GeV}$, and the corresponding vev is $v \sim 246\,\mathrm{GeV}$. The dark scalars from Φ_D are denoted by H, A and $H^{\pm}$; their masses are not determined by direct measurements. Note also that there is no definite CP-quantum number for A, H in this scenario. Due to the $\mathbb{Z}_2$ symmetry, the model contains a stable scalar, which can serve as a dark matter candidate. In the following, we chose H as the DM particle.

The potential is then given by

$$\begin{aligned} V(\Phi_S, \Phi_D) = & -\frac{1}{2}\left[m_{11}^2(\Phi_S^\dagger\Phi_S)+m_{22}^2(\Phi_D^\dagger\Phi_D)\right]+\frac{\lambda_1}{2}(\Phi_S^\dagger\Phi_S)^2+\frac{\lambda_2}{2}(\Phi_D^\dagger\Phi_D)^2 \\ & +\lambda_3(\Phi_S^\dagger\Phi_S)(\Phi_D^\dagger\Phi_D)+\lambda_4(\Phi_S^\dagger\Phi_D)(\Phi_D^\dagger\Phi_S)+\frac{\lambda_5}{2}\left[(\Phi_S^\dagger\Phi_D)^2+(\Phi_D^\dagger\Phi_S)^2\right]. \end{aligned} \tag{3.2}$$

After electroweak symmetry breaking, the model has a priori seven free parameters; however, as discussed above, M_h and v are fixed by experimental measurements, leaving in total five free parameters. We chose them as

$$M_H, M_A, M_{H^\pm}, \lambda_2, \lambda_{345} \equiv \lambda_3+\lambda_4+\lambda_5. \tag{3.3}$$

The model is subject to a large number of theoretical and experimental constraints (see [20,31, 33] for a survey and more recent updates). In general, constraints differ for the region where $M_H > M_h/2$ and $M_H < M_h/2$; in the latter scenario, extremely strong limits stem from a combination of signal strength measurements of the 125 GeV Higgs and dark matter relic density limits. We exemplify this in figure 3, where we show the allowed parameter regions for both cases. For $M_H \geq M_h/2$, relatively strong constraints stem from electroweak precision measurements, parametrized via the oblique parameters S, T, U [49–52][1], and masses of the dark scalars are highly correlated. On the other hand, for $M_H \leq M_h/2$, an interplay of signal strength measurements and dark matter constraints pose the strongest bounds.

The model features interesting signatures at colliders. At hadron colliders,

$$pp \to HA,\, HH^\pm,\, AH^\pm,\, H^+H^-$$

while for e^+e^- colliders we have

$$e^+e^- \to HA,\, H^+H^-.$$

The production at both machines is mainly mediated via electroweak (Drell-Yan) processes, where all couplings are determined by SM quantities in the electroweak sector, such that cross sections mainly depend on the available phase space. Production cross sections for the above processes can reach up to 1 pb at the 13 TeV LHC [55] and $\mathscr{O}(100\,\text{fb})$ at e^+e^- colliders [33]. However, these values are highly dependent on the considered parameter point. The unstable dark scalars dominantly decay via

$$A \to Z^{(*)}H,\, H^\pm \to W^{\pm(*)}H$$

where the on- or offshellness of the electroweak gauge bosons depends on the kinematic features of the considered parameter point.

[1] The values of the oblique parameters as well as other physical observable predictions have been obtained using the Two Higgs Doublet Model Calculator (`2HDMC`) tool [53].

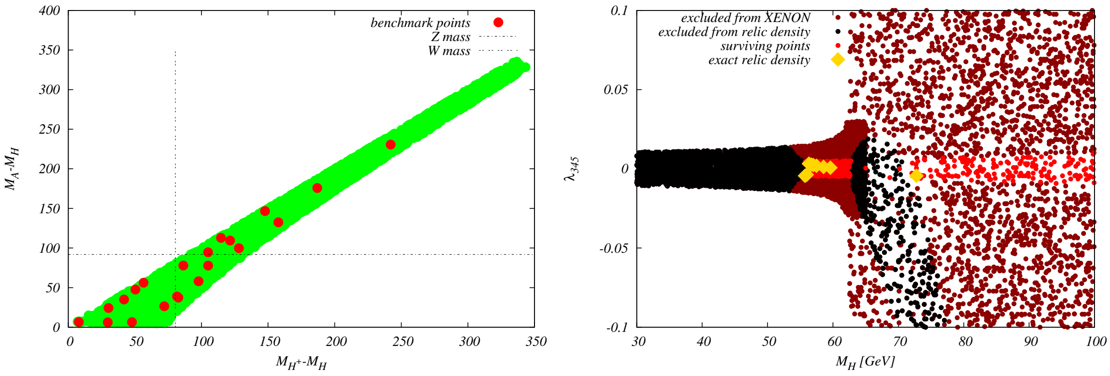

Figure 3: Allowed parameter space in the IDM. *Left:* Allowed parameter range in mass differences from the generic scan presented in [33], with the figure taken from that reference. Benchmark points chosen in that reference are displayed in red. *Right:* allowed parameter region for the case that $M_H \leq 100\,\text{GeV}$, with allowed parameter points displayed in red. The shape for $M_H \leq M_h/2$ is determined by signal strength measurements. Dark matter observables have been obtained using `micrOmegas` [54]. Figure taken from [20].

While the model is not yet directly explored by the LHC experiments, it is interesting to see whether recasts of already existing searches can already cast some light on the possible reach of more dedicated studies. In [40], LHC Run I results in the dilepton channel were used in order to investigate the parameter space of the model; however, most regions that seem to be sensitive to these signatures are already highly constrained by astrophysical measurements. In [34], instead, Run II data for VBF production with of a SM like Higgs with a subsequent invisible decay [56] was used in order to limit the models parameter space. While regions where $M_H < M_2/h$ are strongly constrained by measurements of the invisible branching ratio of h, with the current best limit being $\text{BR}(h \to \text{invisible}) \leq 19\%$ [56][2], the region where H is slightly offshell can be further constrained by a reinterpretation of the corresponding experimental analysis; in general, this recast limits an upper triangle in the (M_H, λ_{345}) plane, see figure 4. This emphasizes the importance of comparing fully simulated samples, including all offshell and interference effects, with current limits from collider searches.

In addition, in [34] it was demonstrated that current 13 TeV multi-lepton searches are not sensitive to the IDM within the allowed parameter regimes. This can be traced back to relatively high cuts on missing transverse energy $\not{E}_\perp$; figure 4 shows that there is an almost log-like decay of the production rates as a function of the available $\not{E}_\perp$ per parameter point. However, an adjustment of the corresponding cuts could in principle open up the according parameter space, enhancing the corresponding signal rates by nearly an order of magnitude. Especially for leptonic final states, this should not pose an impediment on reasonable trigger requirements.

The above example shows that there are viable theoretical models that are well-studied from the theoretical viewpoint and render well-known experimental signatures, that are yet under-investigated

[2]Note that the updated result on the combined limit has been made available in May 2019.

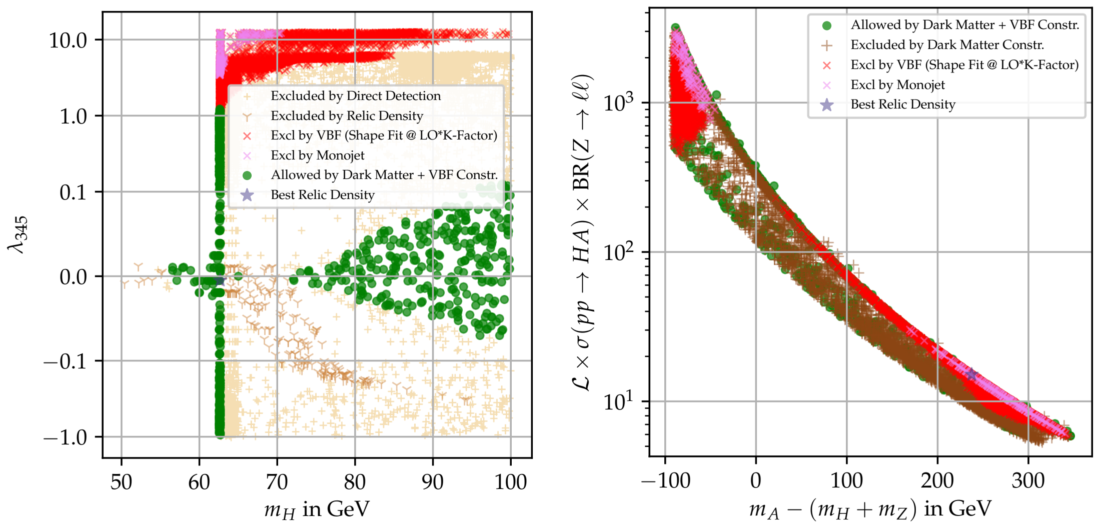

Figure 4: Results of the recast of the Inert Doublet Model, presented in [34]. *Left:* Constraints on the parameter space in the (M_H, λ_{345}) plane taking all theoretical and experimental constraints into account. Recasts of VBF [56] and monojet [57,58] searches are also shown. For $M_h \gtrsim M_h/2$, the VBF recast provides the only constraint in certain regions of parameter space. *Right:* Production cross section for the dilepton and missing transverse energy final state in the IDM, vs. estimate of the available missing transverse energy from kinematic considerations. Cuts on $\not{E}_\perp \gtrsim 100\,\mathrm{GeV}$ reduce the production cross sections by roughly an order of magnitude.

by the LHC experiments. I strongly encourage the experimental collaborations to widen their searches to take such models, including modified cut strategies, into account.

3.2 Future collider prospects

Benchmarks for the investigation of the IDM at e^+e^- colliders, taking all current constraints into account, have been proposed in [33]. Results, based on dedicated simulation of all signal and background processes, with beamstrahlung and detector acceptance taken into account, have been presented in [59, 60] for CLIC running at 380 GeV, 1.5 TeV and 3 TeV (see [61] for an extension of this work to center-of-mass energies of 250 and 500 GeV). The analysis was based on a combination of pre-cuts with the application of boosted decision trees. In general, significances up to ~ 30 can be obtained using these methods, where best results were obtained for mass scales[3] below 500 GeV at $\sqrt{s} = 380\,\mathrm{GeV}$. We investigated $\mu^+\mu^- + \not{E}_\perp$ as well as $e^\pm\mu^\mp + \not{E}_\perp$ final states and found that in general an approximate limit of $\sigma\left(e^+e^- \to \ell\ell' + \not{E}_\perp\right) \sim 1\mathrm{fb}$ can be taken as a lower limit above which discovery seems feasible for integrated luminosities $\int \mathscr{L} = 1\mathrm{ab}^{-1}$. The corresponding results are shown in figure 5[4]. Model implementation and event generation were done making use of a SARAH [63], `SPheno 4.0.3` [64, 65], and `WHizard 2.2.8` [66, 67]. Routines for boosted decision trees were obtained from the TMVA toolkit [68].

[3]Mass scale denotes the sum of the produced dark scalar pair masses.

[4]Note that investigations in the semi-leptonic channel can improve the mass reach by a factor 2; cf. e.g. [62] for a presentation of preliminary results.

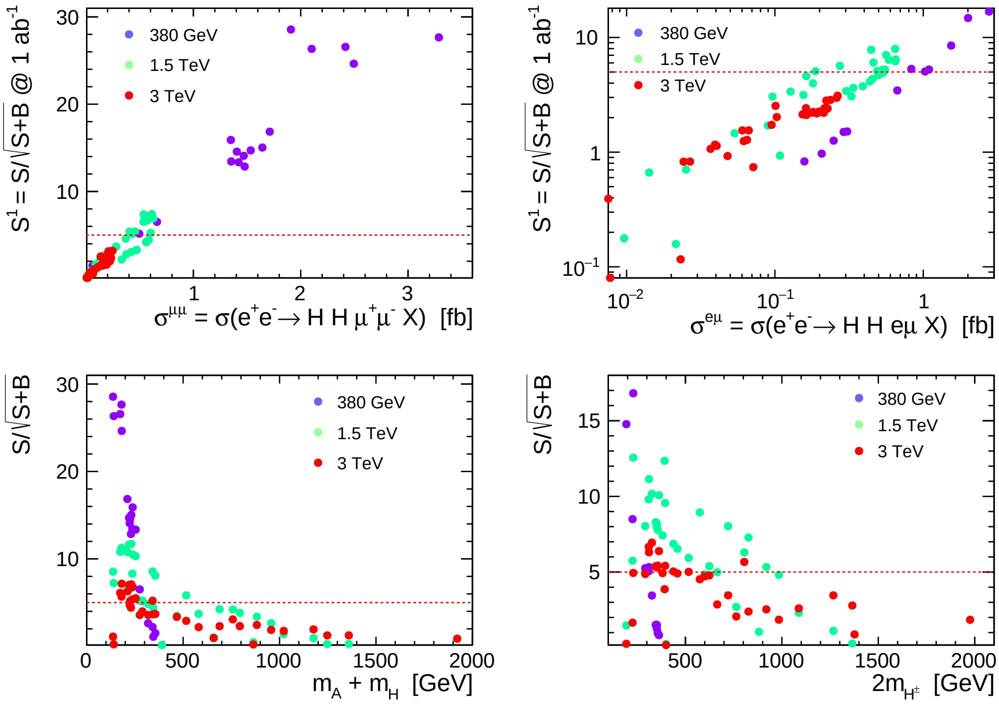

Figure 5: Significances obtained for $e^+e^- \to \ell\ell' + \not{E}_\perp$ final state within the IDM for various center-of-mass energies, resulting from dedicated studies presented in [59]. *Left column:* significances in the $\ell\ell' \equiv \mu^+\mu^-$ channel, with major production mode via HA production. *Top:* Significance at $\int\mathscr{L} = 1\,\mathrm{ab}^{-1}$, for various center-of-mass energies. In general, discovery is possible if $\sigma(e^+e^- \to \mu^+\mu^- + \not{E}_\perp) \gtrsim 1\mathrm{fb}$ prior to cuts. *Bottom:* Significances as a function of the mass scale $M_A + M_H$, with respective integrated target luminosities of $\int\mathscr{L} = (1, 2.5, 5)\,\mathrm{ab}^{-1}$ for $\sqrt{s} = 380\,,\mathrm{GeV}, 1.5\,, 3\,\mathrm{TeV}$. *Right column, top and bottom:* significances in the $\ell\ell' \equiv e^\pm\mu^\mp$ channel, following mainly H^+H^- production. The mass scale in the bottom plot is now given by $2M_{H^\pm}$.

In general, therefore, BSM scenarios where production modes are mainly goverend by electroweak processes also provide an important set of models that can be tested at future e^+e^- colliders down to relatively low production cross sections.

4. Two real scalar extension at hadron colliders

Aside from already explored signatures that might be reinterpreted in or modified for different new physics models, another important topic are signatures which have so far not been explored by the experimental collaborations using the currently available dataset. A prominent example for this are scalar-to-scalar decays. While searches for new physics states that decay into the SM scalar, as well as the decay of the SM scalar into two lighter particles have already been investigated (see e.g. [69–72] for recent searches), single scalar production following by asymmetric scalar decays or symmetric decays, where all scalar masses differ from the SM-like scalar mass at 125 GeV, have not yet been fully explored. Simple counting reveals that for such scenarios at least three physical scalar states need to be present in the model, out of which one takes the role of the state already discovered by the LHC experiments.

The simplest example for such a new physics model is described by the extension of the SM scalar sector by two real (or one complex) scalar(s). The most general model contains in total 21 parameters in the scalar sector [73]; however, additional symmetries can be imposed that lead to a dramatic decrease of the number of free parameters (see e.g. [74, 75]).

We here discuss a model that obeys the $\mathbb{Z}_2 \otimes \mathbb{Z}_2'$ symmetry ${\mathbb{Z}_2}^S : S \to -S, {\mathbb{Z}_2}^X : X \to -X$, while all other fields transform evenly under the respective $\mathbb{Z}_2$ symmetry. This model has recently been discussed in great detail in [76]. The potential in the scalar sector is then given by

$$\begin{aligned} V(\Phi, S, X) = & \mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \mu_S^2 S^2 + \lambda_S S^4 + \mu_X^2 X^2 + \lambda_X X^2 \\ & + \lambda_{\Phi S} \Phi^\dagger \Phi S^2 + \lambda_{\Phi X} \Phi^\dagger \Phi X^2 + \lambda_{SX} S^2 X^2 \,. \end{aligned} \tag{4.1}$$

where Φ denotes the doublet also present in the SM potential and X, S are two additional real scalars that are singlets under the SM gauge groups. All three scalars acquire a vev and mix. This leads to three physical states with all possible scalar-scalar interactions.

The model, including all theoretical and experimental constraints, has been described in [76], which we refer the reader to for further reference. Main constraints stem from the Higgs signal strength measurements by the LHC experiments. We also found that perturbative unitarity as well as boundedness from below pose important constraints, in addition to current collider searches. Results have been obtained using a private version of the `ScannerS` [74, 75, 77, 78] framework.

In the following, we will use the convention that

$$M_1 \leq M_2 \leq M_3 \tag{4.2}$$

and denote the corresponding physical mass eigenstates by h_i. Gauge and mass eigenstates are related via a mixing matrix. Interactions with SM particles are then inherited from the scalar excitation of the doublet via rescaling factors κ_i, such that $g_i^{h_i AB} = \kappa_i \, g_i^{h_i AB, \text{SM}}$ for any $h_i AB$ coupling, where A, B denote SM particles. Orthogonality of the mixing matrix implies $\sum_i \kappa_i^2 = 1$. Furthermore, signal strength measurements require $|\kappa_{125}| \gtrsim 0.96$ [76] for the SM-like scalar h_{125}, which can be h_1, h_2 or h_3 depending on the specific parameter choice.

The model features interesting scalar-to-scalar decays

$$pp \to h_a \, (+X) \to h_b h_b \, (+X), \tag{4.3}$$

$$pp \to h_3 \, (+X) \to h_1 h_2 \, (+X), \tag{4.4}$$

where $a, b \in \{1, 2, 3\}$ under the assumption that the mass hierarchy (4.2) is fulfilled and on-shell decays are kinematically allowed. In [76], six benchmark planes (BPs) were suggested for the decay chains above: three involving asymmetric decays (4.4) and three symmetric decays (4.3), where in the latter case only scenarios were considered where $M_{a,b} \neq 125\,\text{GeV}$. Depending on the specific benchmark point, production rates can reach $\mathcal{O}(60\,\text{pb})$ for the above production modes. The benchmark scenario which considers $h_3 \to h_2 h_2$, where $M_2 > 250\,\text{GeV}$, can furthermore lead to interesting $h_{125} h_{125} h_{125}$ and $h_{125} h_{125} h_{125} h_{125}$ final states. Largest rates for these processes, including further decays to SM final states, are in the $\mathcal{O}(\text{fb})$ range.

Figure 6 shows predicted production rates for several of these benchmark planes: BPs 1/3 for the asymmetric decay, where $h_{125} \equiv h_3/h_1$, as well as two symmetric scenarios BPs 4/ 5 where a non-SM like scalar decays into light scalars with $M_1 \leq 125\,\text{GeV}$. Depending on the benchmark point, dominant final states typically contain multiple b-jets $b\bar{b}b\bar{b}\,(b\bar{b})$. It should also be noted that a small region of parameter space for the symmetric decay $h_3 \to h_2 h_2$ has recently been investigated by the ATLAS experiment in the $W^+W^-W^+W^-$ channel [79].

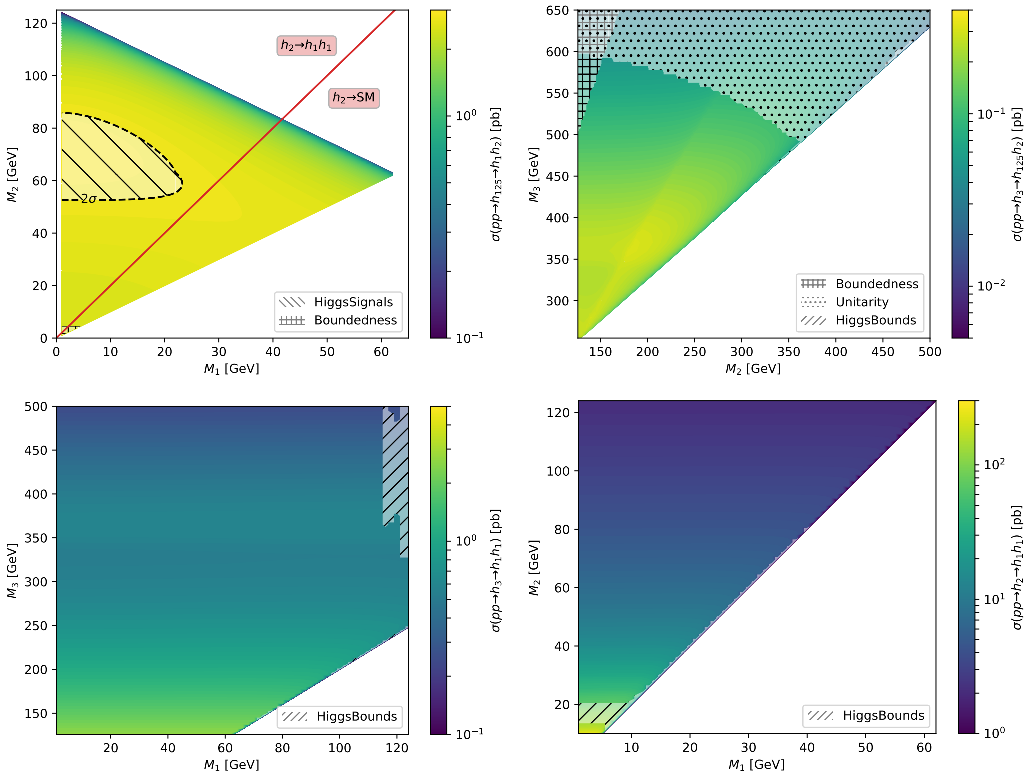

Figure 6: Signal rate predictions for various benchmark planes suggested in [76], at the 13 TeV LHC. Regions forbidden by specific theoretical or experimental constraints are indicated accordingly. *Top left:* BP1, where $M_3 = 125\,\text{GeV}$. Production rates reach $\sim 3\,\text{pb}$, with dominant branching ratios into $b\bar{b}b\bar{b}$ and $b\bar{b}b\bar{b}b\bar{b}$ final states. *Top right:* BP3, where $M_1 = 125\,\text{GeV}$. Production rates reach $\sim 0.3\,\text{pb}$. Dominant branching ratios are to $b\bar{b}W^+W^-$ and $b\bar{b}W^+W^-W^+W^-$, depending on the region in parameter space. *Bottom left:* BP5, where $M_2 = 125\,\text{GeV}$. Production rates reach up to $3\,\text{pb}$. Dominant decays are into $b\bar{b}b\bar{b}$ final states. *Bottom right:* BP4, where $M_3 = 125\,\text{GeV}$. Signal rates can reach up to $60\,\text{pb}$, with dominant decays again leading to $b\bar{b}b\bar{b}$ final states.

The model introduced above renders the simplest extension of SM scalar sector that allows for the new processes (4.3), (4.4). Our recent study has shown that these can lead to sizeable rates at the 13 TeV LHC, while still complying with all current theoretical and experimental bounds. I strongly encourage the experimental collaborations to (further) investigate such scenarios using both current as well as future LHC data.

5. Conclusion

After the discovery of a scalar which so far complies with predictions for a SM Higgs particle within the theoretical and experimental uncertainties, an important quest for the theoretical and

experimental community is to establish whether the discovered particle corresponds to the scalar predicted by the SM, or whether it is part of a more extended scalar sector. I here commented on several scenarios introducing new particle content. The first extends the SM scalar sector by a real scalar which is a singlet under the SM gauge group. This model features a minimal set of additional parameters and therefore provides an ideal testbed to understand the interplay between theoretical and experimental constraints. For this model, direct searches as well as measurements of the Higgs signal strength start to dominate the constraints on the parameter space up to scalar masses $M_H \lesssim 1\,\text{TeV}$, while electroweak precision measurements as well as theoretical bounds also provide important constraints in some of the parameter space. In addition, I discussed the Inert Doublet Model, a two Higgs model that provides a dark matter candidate. This model has so far not directly been explored by the LHC experiments. Although production rates could in principle lead to a sizeable number of new physics particles already within the current dataset, current searches for similar final states would have to be modified in order to increase sensitivity for this model. In contrast, dedicated studies of this model at future e^+e^- facilities indicate that several signatures could be explored at such machines, with mass scales $\lesssim 500\,\text{GeV}$ being accessible using the leptonic channel. For high energy CLIC stages, this reach is expected to be extended up to about 1 TeV when the semi-leptonic channel is considered. Similar dedicated experimental studies should be performed within a hadron collider framework. Finally, I have commented on a model that renders novel scalar-to-scalar decays, with signatures so far not extensively explored by the experimental community. These symmetric or asymmetric decays discussed here can render relatively high cross sections, up to $\mathcal{O}\,(60\,\text{pb})$ depending on the chosen parameter point and benchmark scenario. These certainly should be explored in more detail within the near future.
In summary, while the experimental collaborations have already constrained a larger number of models with extended scalar sectors in many dedicated experimental studies, many open questions still remain. It is imminent that the currently available Run-II dataset should be explored for the modified or new searches discussed here, and that insight from such studies should be used to further design search strategies at future colliders. In addition, it is important to investigate the discovery potential of future $e^+\,e^-$ colliders for these models.

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