Abstract

I will show, via effective field theory (EFT) techniques, that obtaining an observationally consistent relic density while evading stringent direct detection limits and maintaining $h_{125}$ phenomenology in an extended Higgs sector can be easily achieved. I will then map such an EFT to the low energy limit of the NMSSM with the Higgsinos integrated out. Both the singlino and the singlet-like CP-odd and even scalars in the NMSSM may play a relevant role in such a scenario, while being difficult to probe via conventional searches. The singlet sector of the general NMSSM can be mapped on to a 2HDM+S, and I will discuss prospects of probing this at the LHC using signatures such as mono-Higgs and mono-Z. This proceeding is mostly based on Refs. [1] and [2].

Keywords: Higgs, NMSSM, Dark Matter, Direct Detection, EFT

1. Introduction

In recent years the WIMP paradigm has become increasingly unpopular due to the stringent limits being placed on the spin-independent direct detection (SIDD) scattering cross section of dark matter (DM) with nuclei from experiments such as XENON1T [3]. Analogously, the null direct search results at the LHC, and the so far very Standard Model (SM) like nature of $h_{125}$ has lead to a general pessimism in our field regarding the existence of an extended Higgs sector. However, if certain relationships between model parameters are fulfilled, it is easy to evade both $h_{125}$ considerations and dark matter scattering limits, while obtaining an observationally consistent dark matter relic density. Ultimately we are in search of the ultraviolet (UV) completion of the SM, which we expect to be based on symmetries at the UV scale. In such a case it is not difficult to imagine that low-scale physics may show up as having certain “fine-tuned” relations. Keeping an agnostic attitude towards such symmetries, one can nevertheless investigate the requirements for the parameters of a model such that our current lack of experimental signals is not due to the absence of new physics (NP) at the weak-scale, but rather because certain relationships exits making NP challenging to discover with conventional means.

In Sec. 2 I present a minimal scenario for obtaining a consistent relic density and a suppressed SIDD cross-section from an extended Higgs sector and an additional SM singlet playing the role of DM, using the language of EFT. I show that these requirements can be easily fulfilled without any unnatural hierarchies in the model parameters or physical properties. Sec. 3 outlines LHC search strategies and their prospects which may be used to probe such a scenario. I then show in Sec. 4 how such a model is mapped onto the Next to Minimal Su-
persymmetric Standard Model (NMSSM). I summarize in Sec. 5.

2. EFT for Higgs Couplings to Dark Matter

I will discuss a model with a SM singlet Majorana fermion DM \( \chi \), which has no renormalizable interactions with SM particles. In order to couple DM to the SM, we consider the Higgs sector of a Type II Two Higgs doublet model (2HDM): \( H_u \) and \( H_d \).

Assuming, as usual, that both Higgs doublets acquire vacuum expectation values (vevs), \( \langle H_d \rangle = v_d \), \( \langle H_u \rangle = v_u \), with \( v_d^2 + v_u^2 = (174 \text{ GeV})^2 \) and \( \tan \beta = v_u/v_d \), I define the Higgs basis \( \{ 4, 5 \} [6, 7, 8, 9, 10] \) such that the mass eigenstate \( H^{\text{SM}} \) (associated with the observed 125 GeV Higgs boson) has completely standard model couplings, i.e. the SM vev is acquired by the field corresponding to the neutral component of \( H^{\text{SM}} \), hence \( \langle H^{\text{SM}} \rangle = \sqrt{2} v \) and \( \langle H^{\text{NSM}} \rangle = 0 \):

\[
H^{\text{SM}} = \sqrt{2} \text{Re} \left( \sin \beta H_0^u + \cos \beta H_0^d \right), \tag{1}
\]

\[
G^0 = \sqrt{2} \text{Im} \left( \sin \beta H_0^u - \cos \beta H_0^d \right), \tag{2}
\]

\[
H^{\text{NSM}} = \sqrt{2} \text{Re} \left( \cos \beta H_0^u - \sin \beta H_0^d \right), \tag{3}
\]

\[
A^{\text{NSM}} = \sqrt{2} \text{Im} \left( \cos \beta H_0^u + \sin \beta H_0^d \right). \tag{4}
\]

In addition, we impose that there are no explicit mass terms or scales and hence the Lagrangian is scale invariant. The absence of explicit scale dependence could be originating from a \( Z_2 \) symmetry. In such a situation, a natural way to generate the mass \( m_\chi \) and the scale of NP \( \mu \) is via the vev of a singlet \( S = \langle S \rangle + \frac{1}{\sqrt{2}} \left( H^S + i A^S \right) \).

Hence, without loss of generality we can define \( m_\chi = 2\kappa \langle S \rangle \) and \( \mu = \lambda \langle S \rangle \), where \( \kappa \) and \( \lambda \) are dimensionless parameters.

Assuming that \( d > 4 \) terms originate from a theory where a heavier \( SU(2) \)-doublet Dirac fermion with mass \( \mu \) has been integrated out, we can write all the allowed \( d = 6 \) operators which would arise from integrating out such a field, describing the interactions of a Majorana fermion \( \chi \) with the two Higgs doublets \( H_u \), \( H_d \).

Ignoring the charged gauge boson interactions, we get

\[
\mathcal{L} = -\frac{\delta \chi \chi}{\mu} \left( H_u^* H_d \right) \left( 1 - \frac{i \lambda S}{\mu} \right)
- \kappa S \chi \chi \left( 1 + \frac{H_u^0 H_d + H_d^0 H_u}{|\mu|^2} \right) + \text{h.c.}
+ \frac{\alpha}{|\mu|^2} \left( \chi H_u^0 H_u + \text{h.c.} \right)
\]

\[
= \left( \chi H_u^0 \delta^\mu \left[ \frac{g_1}{s_w} (T_3 - Q_\chi W_3) Z_\mu \right] (\chi H_u)
+ \chi H_d^0 \delta^\mu \left[ \frac{g_2}{c_w} (T_3 + Q_\chi W_3) Z_\mu \right] (\chi H_d)
\right)
\]
ever, we see that we can obtain a blind spot for the can-

hination of the DM particles into Ω

annihilation cross-section needed for obtaining an ob-

the extended Higgs sector states to DM, mediating the

pressed. In fact there can be significant couplings of

other CP-even Higgs bosons.

In proximity to such a blind spot, there can be further

suppression of the SIDD due to interference with the

other CP-even Higgs bosons.

Note that the couplings to the other Higgs states, in-

cluding the Goldstone modes, are not necessarily sup-

pressed. In fact there can be significant couplings of the

extended Higgs sector states to DM, mediating the annihilation cross-section needed for obtaining an ob-

servationally consistent relic density. It turns out that Ωh^2 \sim 0.12 can be easily achieved by the s-channel annih-

lation of the DM particles into H mediated by G^0 for the

region of masses we are investigating.

An example for couplings of the Higgs sector states to

DM where the SIDD is suppressed while simultane-

ously obtaining a consistent relic density is shown in

Fig. 2. The mass spectrum is fixed to labeled values.

Changing these values would change the precise num-

erical values shown, but the qualitative behavior remains

the same. I stress that neither the couplings nor the EFT

parameters have any extreme values. While specific re-

lationships between parameters have to be fulfilled, the

resulting scenario does not appear to be particularly dif-

ficult to achieve.

I have discussed how to obtain a WIMP with ther-

mally produced relic density whose direct detection is

suppressed, in conjunction with a Higgs sector which is

aligned so that h_{125} phenomenology is completely SM

like. The couplings between the Higgs states don’t play

a role in the scenario discussed so far. However, the
details of the Higgs scalar potential may be relevant for

the discovery prospects for such a scenario, and some
possibilities will be discussed in the next sections.

3. Higgs Phenomenology & LHC prospects

The scalar potential for a 2HDM + S is given in

Refs. [11, 2]. The generic potential is described by 27

arbitrary parameters and at first glance appears difficult
to analyze. However the 125 GeV Higgs mass and its

SM-like couplings enable us to constrain these signif-

icantly. In particular, we show that most of the rele-

vant phenomenology can be parameterized in terms of

mostly the physical parameters like masses and mixing

angles [2].

I highlight first a few conditions that alignment im-

poses on the phenomenology. The most important thing

is that alignment forbids the coupling of the NSM or

S like CP-even Higgs bosons from coupling to pairs of

h_{125} or vector bosons (W or Z). Additionally the

CP-odd state couplings to h_{125} and Z are also for-

bidden. Instead, there can be interesting Higgs cascade

decays of the heavy Higgs bosons to final states involv-

ing only one h_{125} or a Z such as (H^{NSM} \rightarrow H^S H^{SM}) or

(A^{NSM} \rightarrow H^S Z). The singlets couple only to DM or to

the SM particles via their mixing with the other states.

Hence depending on the mixing angles and the arbitrary
coupling to the DM, such decays could result in h_{125} or

Z plus visible or invisible signatures.

We collected all the current search results and projec-
tions available for the relevant decays, as well as per-
formed detailed collider simulations where needed, to

obtain the projection for the reach at the LHC with 3000

fb^{-1} of data. I present an example of the reach we ob-
tain for exemplary scenarios in Figs. 3 and 4. As can be

seen, combining the different searches for the various

Higgs cascade decay modes provides coverage of most

of the parameter space at low values of tanβ, a region

which is generally challenging to probe [2].

4. NMSSM Interpretation

The Next to Minimal Supersymmetric Standard

Model (NMSSM) is a well motivated extension of the

SM. The NMSSM has a 2HDM + Singlet (S) scalar

sector, analogous to the Higgs sector assumed in the

previous section. What makes the NMSSM particu-

larly interesting is that a Higgs boson with a mass of

125 GeV and SM-like couplings is easily and naturally

obtained [11]. The NMSSM provides two SM Ma-

jorana singlets which may play the role of DM, the

\[
\begin{align*}
+ \chi^i H_d^\beta \mu \left[ i \partial_\mu - \frac{g_1}{s_w} (T_3 - Q_3^2) Z_\mu \right] (\chi H_d),
\end{align*}
\]

where \( S = \mu / \lambda + S, Q \) and \( T_3 \) are the charge and weak

isospin operators, \( s_w \equiv \sin \theta_W \) with the weak mixing

angle \( \theta_W \), and \( g_1 = e / \cos \theta_W \) is the hypercharge
coupling.

From Eqs. (1) and (5), the coupling of the DM parti-
cles to the SM-like Higgs is

\[
g_{\chi h} \simeq g_{\chi H^{SM}} = \sqrt{2} \frac{\delta \sin 2\beta - \frac{(\xi - \alpha) m_h}{\mu^2} }{\mu}.
\]

The SIDD scattering cross-section is mediated by the
t-channel exchange of the CP-even scalars. Generically, the

SM-like Higgs has the dominant contribution. How-

dever, we see that we can obtain a blind spot for the can-

cellation of the coupling of \( H^{SM} \) to pairs of DM occurs for

\[
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obtained [11]. The NMSSM provides two SM Ma-

jorana singlets which may play the role of DM, the
singlino (superpartner of the Singlet Higgs) and the bino (superpartner of the hypercharge gauge boson). Due to SUSY relations, phenomenological considerations of the $h_{125}$ correlate the masses of all the scalars as well as that of the Singlinos and the Higgsinos, leading to a consistent scenario where the entire Higgs sector as well as the DM candidates can be mapped to the NMSSM in the following two regions [11]:

- For Singlino DM, we can map the couplings in Eq. (5) directly to those in the NMSSM via

$$\delta = -\alpha \to -\lambda^2, \lambda \to \lambda, \kappa \to \kappa, \xi \to 0. \quad (8)$$

The mapping above leads to the blind spot condition [cf. Eq. (7)]

$$\sin 2\beta = m_{\chi}/\mu. \quad (9)$$

- In contrast to the singlino, the bino couples to different combinations of the Higgs doublets and the singlet. Such interactions would be obtained by writing down the EFT for the Higgs doublets and the singlet transforming under the $Z_1$, while assuming the Majorana fermion $\chi$ transforms trivially and has a Majorana mass $m_{\chi} = M_1$. Keeping this in mind, we can map the couplings of the bino to those in the EFT, Eq. (5), via

$$\delta = \alpha \to \frac{\rho^2}{2}, \lambda \to \lambda, \kappa \to \kappa, \xi \to 0. \quad (10)$$

The blind spot condition for the bino region is then

$$\sin 2\beta = -m_{\chi}/\mu. \quad (11)$$

We ran numerical scan using NMSSMTools and MicrOmegas validating our expectation for the obtaining of a DM with suppressed SIDD due to the presence of blindspots as dictated by Eqs. (9) and (11). The results are shown in Fig. 5. We also observed that while the SIDD can be easily suppressed while obtaining the correct relic density, their is no such suppression mechanism for the spin dependent direct detection (SDDD) cross section. In fact, while certainly the limits for SDDD are much weaker, near future prospects may allow us to probe most of the region of parameter space with very suppressed SIDD. This is shown in Fig. 5 where the SDDD is seen to be at most two orders of magnitude below current limits.

As mentioned earlier, the NMSSM Higgs sector is very predictive due to the presence of a SM-like $h_{125}$. We investigated the collider phenomenology associated with the Higgs sector in detail. The prospects for discovery for the scenarios with at least one mass lighter
than 1 TeV are shown in Fig. 7 [15]. This shows in particular that the Higgs cascade decays channels discussed in the previous section can provide complementary probes to the standard search channels, bringing most of the interesting parameter regions within reach of the high luminosity LHC.

5. Summary

There has been no compelling evidence for the presence of NP at the weak scale since the Higgs discovery in 2012. This has lead to wide spread pessimism in our field regarding both the WIMP paradigm and the most popular SUSY models. In these proceedings I have presented a simple scenario where vanilla WIMP DM with thermal relic density can easily evade the stringent SIDD bounds. Using an EFT formulation I present parameter relations such that the coupling of DM can be suppressed to \( h_{125} \) while maintaining enough DM-SM interactions such that thermal equilibrium can be maintained. Given that the DM candidate is assumed to be a SM singlet, coupled with the constraints imposed by the alignment of the Higgs vacuum expectation value on an extended Higgs sector, standard search strategies at the LHC may be insensitive to NP. However, Higgs cascade channels which are unsuppressed due to the presence of the singlet scalars, may be provide an additional handle, allowing us to probe much of the relevant parameter region at the LHC.

I then present the mapping of the EFT to the NMSSM, showing that the EFT expectations are borne...
out using sophisticated numerical packages available. I also show the direct detection and LHC prospects for the parameter regions discussed.

I stress that the consistent region of parameters we obtain using both the EFT, and its mapping to the NMSSM, do not require any extreme choices. Indeed this region of parameters would be considered quite “natural”. That said, specific correlations between various parameters are needed. However, considering physics from the UV prospective, it may very well be that GUT scale symmetries broken near the weak scale would show up in low energy physics as strange cancellations or relationships between parameters. Nature may well have chosen to put NP at an energy scale out of our foreseeable reach, which would be our misfortune. However, it seems as likely that there may be NP at the weak scale, and we may have to be more creative to find it.

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