Identifying Minimal Composite Dark Matter

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Abstract
We attempt to identify the minimal composite scalar dark matter from strong dynamics with the characteristic mass of order TeV scale. We provide direct and indirect limits from dark matter direct detections and collider facilities. Compared to a fundamental scalar dark matter, our results show that in the composite case with sizable derivative interaction between the dark matter and Higgs, the disappearing resonant mass region, the smaller spin-independent dark matter-nucleon scattering cross section in certain dark mass region, and the absence at the HL-LHC provide us an opportunity to distinguish the composite dark matter.

Keywords Direct detection · Composite dark matter · HL-LHC

1 Introduction
The Higgs boson play a very broad role in theoretical physics, such as the source of mass [1] and the expansion of the universe [2, 3]. Although a Higgs-like boson [4, 5] in the standard model has been established by the LHC, there is still a lack of enough information about the “nature” of the observed Higgs. Whether it is a fundamental or a composite state is critical as it points to totally different new physics respect to the electroweak symmetry breaking. This question will be addressed by near future precision measurements on the Higgs at HL-LHC [6]. Similarly, there are also different choices on the thermal dark matter (DM), which can be either fundamental or composite. Since both the observed Higgs and yet confirmed DM are often simultaneously delivered by a single “dark” sector behind the electroweak symmetry breaking, instead of conventional choice [7] in this paper we will explore both a composite Higgs and a composite scalar dark matter (CSDM).

In this scenario, the well-known hierarchy problem is solved by identifying both of these scalars as pseudo-Nambu-Goldstone (PNG) bosons [8–10] tied to some global symmetry. The main idea behind Composite Higgs models (CHM) is that the Higgs boson could emerge...
as a bound state of a strongly interacting sector, instead of being an elementary scalar. For reviews, see, e.g. [11, 12]. Following the spirit of simplicity, we consider the minimal CSDM with the following features.

- The minimal structure of the coset which is suitable for both composite Higgs $h$ and CSDM $\eta$ is $\text{SO}(6)/\text{SO}(5)$ [13] based on the minimal composite Higgs model [14]. For recent discussions about alternative models, see e.g., [15–17].
- The minimal matter content in the effective theory of the composite sector contains only the light composite Higgs and CSDM, with the other freedoms therein decoupled.
- The minimal representation of the composite fermions corresponds to the fundamental representation of $\text{SO}(6)$.

The features above yield the following effective Lagrangian\(^1\) for the PNG bosons in the minimal CSDM model

$$L_{\text{eff}} = \frac{1}{2} \left( \partial_\mu h \right)^2 - \frac{1}{2} m_h^2 h^2 - \frac{\lambda_h}{2} h^3 - \frac{\lambda_h^4}{4} h^4 + \frac{1}{2} \left( \partial_\mu \eta \right)^2 - \frac{1}{2} m_\eta^2 \eta^2 - \frac{\lambda_\eta}{4} \eta^4 + L_f + L_V - L_h + \cdots,$$

with

$$L_h = \frac{\kappa_1}{2} \eta h^2 + \frac{\kappa_2}{4} \eta^2 \eta^2 - \left( \partial_\mu h \partial^\mu \eta \right) \left[ \frac{\xi}{\sqrt{1 - \xi}} \frac{\eta}{\nu} + \frac{\eta (1 + \xi)}{1 - \xi} \right],$$

$$L_f = -m_\psi \bar{\psi} \psi \left[ 1 + \frac{1 - 2 \xi}{\sqrt{1 - \xi}} \frac{h}{\nu} - \frac{(3 - 2 \xi) \xi h^2}{2 (1 - \xi) \nu^2} - \frac{\xi}{1 - \xi} \right],$$

$$L_V = \left( m_W^2 W_\mu^+ W^- \mu + \frac{m_Z^2}{2} Z_\mu Z^\mu \right) \left[ 1 + \frac{h^2}{\nu} + (1 - \xi) \right],$$

where the constrained parametrization [20, 21] has been adopted, the Higgs mass $m_h = 125$ GeV, $m_\eta$ is the CSDM mass, and $\xi = \nu^2 / f^2$ with the weak scale $\nu = 246$ GeV and $f$ referring to the breaking scale of $\text{SO}(6)$. We have neglected the next-to-leading-order terms, which is because electroweak precision measurements require $\xi \ll 1$ [22]. The derivative self interactions of the composite Higgs has no contribution in this work, and certain hidden parity such as $Z_2$ [13] with $\eta$ odd and the SM particles even in order to ensure the stability of $\eta$. Apart from the self interaction for $\eta$, which is actually decoupled from both the DM relic abundance constraint and DM direction detections, there are only three free parameters in (1)-(4), as composed of the CSDM mass $m_\eta$, the Higgs portal coupling $\kappa_1 = \kappa \sqrt{1 - \xi}$ and $\kappa_2 = \kappa (1 - \xi)$, and the composite mass scale $f$ or equivalently $\xi$, which are responsible for phenomenologies of the minimal CSDM. Although this observation is made in the constrained parametrization, it is also true in the other parameterizations, see e.g. [21].

Unlike previous literature [20, 21], on the one hand, we have updated the previous space restrictions by using the latest direct detection experiments data; On the other hand, we

\(^1\) Firstly, we use Goldstone matrix to describe PNG bosons, then derive kinetical terms in terms of Callan-Coleman-Wess-Zumino (CCWZ) formalism [18, 19], and finally calculate interactions between the PNG bosons and SM fermions as well as effective potential in terms of spurion method (see, e.g. [11]).
have conducted a more complete analysis, including direct detection, indirect detection and collider detection. The framework of parametrization as above enables us to estimate the general phenomenological status of the minimal CSDM. In Section 2, we will analyze the constraints on the CSDM from the latest DM direct detection limits. Then, in Section 3 we turn to indirect constraints both from DM and collider experiments, where the latest precision tests on the Higgs at the LHC are able to place strong indirect constraint on the parameter space. Section 4 is devoted to the direct probes of CSDM at the LHC. During the study, we will point out the important differences between the CSDM and the fundamental scalar dark matter (FSDM) [23, 24] (for review, see e.g. [25]). We present the final results and conclude in Section 5.

2 DM Phenomenology

2.1 Parameter Space of Dark Matter

Instead of fixing $\kappa$ as in ref. [21], which results from certain specific assumptions on the composite fermions in the composite sector, we take it as a free parameter with rational values. A relaxation on the parameter $\kappa$ gives rise to a parameter space of thermal DM obviously larger than that in ref. [21].

Apart from a partial of interactions similar to that of FSDM [25, 26] in (2), $L_h$ also contains the derivative interactions with momentum dependence, which lead to significant deviation from the FSDM for $f$ of order TeV scale. The derivative interactions contribute to $\eta\eta$ annihilation cross section in the manner that it grows as the DM mass increases, which can be interpreted from the modifications to the effective couplings in (2):

$$\kappa_1 \approx \kappa - 2\xi \left( \frac{m_\eta^2}{v^2} \right) + \mathcal{O}(\xi^2),$$

$$\kappa_2 \approx \kappa - 8\xi \left( \frac{m_\eta^2}{v^2} \right) + \mathcal{O}(\xi^2).$$

In (5), the deviations are small in the limit $f \to \infty$, which corresponds to the FSDM as shown by the black curve in Fig. 1. In contrast, the deviation is expected to be large in the case of small $f$, under which $\kappa$ shifts from the value $\kappa^\star$ [25, 26] referring to the FSDM as

$$\kappa \approx \left\{ \begin{array}{ll} \frac{2m_\eta^2}{v^2} \xi & \text{if both solutions exist}, \\
-\frac{2m_\eta^2}{v^2} \xi & \text{if only one solution exists}. \end{array} \right.$$
value of $\kappa$ is allowed as shown in Fig. 1. Due to the derivative interaction, the well-known resonant mass window $m_\eta \sim m_h/2$ gradually disappears as $f$ approaches to smaller value. Similar result has been also reported by [20, 21].

In the discussion above, we have neglected the contribution to the DM annihilation cross section from the contact interaction in (3), which is given by,

$$
\sigma(\eta\eta \rightarrow \bar{\psi}\psi)v_{\text{rel}} \approx \frac{\bar{\xi}^2}{16\pi} \frac{m_\psi^2}{\upsigma^4} \left(1 - \frac{m_\psi^2}{m_\eta^2}\right)^{3/2}.
$$

(7)

Because of the fermion mass suppression in (7), the contribution can be indeed ignored in the CSDM mass range $m_\eta < m_t$. Even for the CSDM mass range $m_\eta > m_t$, as covered by the case with $f = 2$ TeV in Fig. 1, $\sigma(\eta\eta \rightarrow \bar{\psi}\psi)v_{\text{rel}}$ is small compared to the inferred value $\langle \sigma v_{\text{rel}} \rangle \approx 3 \times 10^{-26}\text{cm}^3\text{s}^{-1}$, which indicates that the previous estimate on the behavior of this curve is still valid.

2.2 Direct Detection

Combing the Higgs-portal interaction in (2) and the contact interaction in (3) yield the spin-independent (SI) scattering cross section for the CSDM

$$
\sigma_{\text{SI}} = \frac{f_N^2}{4\pi} \frac{\mu^2 m_N^2}{m_\eta^2} \left(\frac{\kappa(1 - 2\xi)}{m_h^2} + \frac{\xi}{(1 - \xi)v^2}\right)^2.
$$

(8)
where $m_N$ is the nucleon mass, $\mu = m_\eta m_N/(m_\eta + m_N)$ is the DM-nucleon reduced mass, and $f_N \approx 0.3$ is the hadron matrix element. Unlike the preceding analysis on the DM relic abundance, the corrections to (8) due to the derivative interactions are negligible.

Figure 2 explicitly shows the numerical results about the SI cross sections extracted from the DM parameter space in Fig. 1. In this figure, one finds that unlike the FSDM, in which DM mass below $\sim 700$ GeV is nearly excluded by the latest XENON1T limit [29], a large part of the CSDM mass window between $\sim 63 - 416$ GeV is still beneath the latest XENON1T limit [29] and LZ(2022) experiment [30]. With the help of the direct detection experiment, we updated the survival range of the model parameter space. For example, the critical bound for $f = 500$ GeV has been altered from $m_\eta \sim 70$ GeV by XENON100 limit [20] to be nearly excluded by the XENON1T limit, whereas the critical bound for $f = 1$ TeV has been changed from $\sim 200$ GeV by LUX 2013 limit [21] to $\sim 150$ GeV by the XENON1T limit. Therefore, the future XENON1T or LZ results in the large mass window can be useful in distinguishing the CSDM from the FSDM.

3 Indirect Constraints

3.1 DM Annihilation

Astrophysical observations from DM annihilation can be used to indirectly constrain the thermal DM. For DM annihilation into $\gamma$ ray the cross section can be calculated via standard
The averaged cross sections of $\langle \sigma_{\gamma\gamma\nu_{\text{rel}}} \rangle$ (left) and $\langle \sigma_{b\bar{b}\nu_{\text{rel}}} \rangle$ (right) for various scales $f$ as in Fig. 1. While the $\gamma$ ray is weak, the $b\bar{b}$ limit from Fermi-LAT excludes CSDM mass regions $m_\eta \leq 47$ GeV and $63 \geq m_\eta \leq 67$ GeV.

Formula [31],

$$\langle \sigma_{\gamma\gamma\nu_{\text{rel}}} \rangle = \frac{x}{16m_\eta^2K_2^2(x)} \times \int_4^{\infty} ds \sqrt{s-4m_\eta^2s} K_1 \left( x\sqrt{s/m_\eta} \right) \sigma_{\gamma\gamma\nu_{\text{rel}}},$$

(9)

where $x = m_\eta/T$, $s$ is the square of the center-of-mass energy, and $K_1$ and $K_2$ are modified Bessel functions of the second kind. In (9), the annihilation cross section reads as,

$$\sigma_{\gamma\gamma\nu_{\text{rel}}} = \frac{2v^2}{\sqrt{s}} \left( \kappa - \frac{2m_\eta^2}{v^2} \xi \right)^2 \frac{\Gamma_{h\rightarrow\gamma\gamma}}{(s-m_h^2)^2 + m_h^2\Gamma_h^2},$$

(10)

where $\Gamma_h \approx 4.15$ MeV is the total decay width for the SM-like Higgs, and $\Gamma_{h\rightarrow\gamma\gamma}$ is mainly determined by two types of one-loop Feynman diagrams with either virtual vector bosons or fermions [32], whose couplings to the Higgs are corrected by factor $(1 - 2\xi)/\sqrt{1 - \xi}$ and $\sqrt{1 - \xi}$, respectively.

Apart from the $\gamma$ ray, DM annihilation into $b\bar{b}$ can also place constraint. We obtain the cross section $\langle \sigma_{b\bar{b}\nu_{\text{rel}}} \rangle$ in terms of replacing $\sigma_{\gamma\gamma\nu_{\text{rel}}}$ in (9) by [20]

$$\sigma_{b\bar{b}\nu_{\text{rel}}} \approx \frac{3m_h^2}{\pi f^4} \left[ \frac{1}{4} + \frac{1}{4} \left( \frac{s-m_h^2}{\Gamma_h^2 + m_h^2} \right)^2 + \frac{1}{2} \left( \frac{s-m_h^2}{\Gamma_h^2 + m_h^2} \right)^2 \right],$$

(11)

where the first, the second and the last term arise from the contact interaction, the exchange of Higgs and the interference effect, respectively.

Substituting the correlated values of $m_\eta$ and $\kappa$ in Fig. 1 into (9), we show in Fig. 3 the numerical results of $\langle \sigma_{\gamma\gamma\nu_{\text{rel}}} \rangle$ and $\langle \sigma_{b\bar{b}\nu_{\text{rel}}} \rangle$ for the representative values of $f$ in Fig. 1, where the Fermi-LAT [33, 34] and HESS [35] limits are shown simultaneously. Compared to the FSDM, both the values of $\langle \sigma_{\gamma\gamma\nu_{\text{rel}}} \rangle$ and $\langle \sigma_{b\bar{b}\nu_{\text{rel}}} \rangle$ in the case of CSDM are nearly the same in
The Higgs couplings for the representative values of $f$ in Fig. 1, where both the 68% and 95% contours of the best fits values of $k_F$ and $k_V$ are shown for comparison and the values of $f$ in unit of TeV at the crossing points are explicitly shown. We have taken the best fits to these Yukawa coupling constants reported in [36, 37].

The small $m_\eta$ region. While the $\gamma$ ray is weak, the $b\bar{b}$ limit from Fermi-LAT excludes CSDM mass regions $m_\eta \leq 47$ GeV and $63$ GeV $\leq m_\eta \leq 67$ GeV.

### 3.2 Precision Test on Higgs Couplings

The precision measurements on the Higgs couplings are able to effectively constrain the parameter range of $f$. According to the features of the composite Higgs couplings in (3)-(4), we use the conventional two-parametrization fit for our analysis, under which we have

$$k_V = \sqrt{1 - \xi}, \quad k_F = \frac{1 - 2\xi}{\sqrt{1 - \xi}}. \quad (12)$$

Figure 4 shows the constraint on $f$ from the latest 13-TeV LHC data, where the ATLAS best fits are given by $k_V = 1.05$ and $k_F = 1.05$ [36] and the CMS best fits are given by $k_V = 1.08$ and $k_F = 1.06$ [37] respectively. This figure indicates that the latest ATLAS and CMS results have excluded the parameter range $f < 0.86$ TeV and $f < 1.21$ TeV at 95% CL, respectively. These lower bounds will be significantly improved at the future LHC, which makes the precision tests on the Higgs couplings more competitive\(^{2}\) than the precision measurements on the electroweak observables [38]. In what follows, we will not discuss the case with $f = 500$ GeV.

\(^{2}\) Although strong, this indirect constraint may be however evaded in the situation with either non-minimal matter content or non-fundamental representation for the composite fermions.
3.3 Precision Test on Higgs Decay

In the CSDM mass region with $m_\eta < m_h/2$, the composite Higgs can directly decay into the $\eta$ pair either via the Higgs portal interactions in (2) or the contact interactions in (3). The derivative interactions in (2) result in a modification to the effective coupling in the Higgs invisible decay, while the contact interactions contribute to Higgs invisible decay mainly through top quark induced process. All of the loop effects are controlled by the magnitude of $\xi$. Without the loop effect, the decay width is approximated as

$$\Gamma(h \rightarrow \eta\eta) \approx \frac{v^2}{32\pi m_h} \left(\kappa - \frac{2m_h^2}{v^2} \xi \right)^2 \sqrt{1 - \frac{4m_\eta^2}{m_h^2}}.$$  \hspace{1cm} (13)

We show in Fig. 5 the contours of the latest experimental bound on the Higgs invisible decay width $\text{Br}(h \rightarrow \eta\eta) \leq 16\%$ at 68\% CL [39] for the representative values of $f$ as in Fig. 1, above which the CSDM mass region is excluded. Compared to the FSDM, this constraint on the CSDM is slightly weaker. The reason is due to a mild cancellation between the two classes of interactions in (13) given nearly the same $\kappa$ in the mass region $m_\eta < m_h/2$ regardless of the value of $f$, see (1). As a result, the constraint from the Higgs invisible decay is relaxed for finite $f$. Nevertheless, the absence of the resonant mass region for small $f$ makes this relaxation useless.

The observation holds even with the loop effects taken into account. For example, the top-loop induced contribution modifies $\kappa$ in (13) by a factor $\sim \xi \left(\frac{m_t}{v}\right)^3 \log\left(\frac{m_t}{\mu}\right)$, with $\mu$ a cut-off scale. For $f$ larger than 1 TeV, it is obviously smaller than $\kappa$.

**Fig. 5** Same as Fig. 1 with the contours of Higgs invisible decay width $\text{Br}(h \rightarrow \eta\eta) = 16\%$ at 68 \% CL [39] (in dotted), above which the CSDM mass region is excluded.
4 Direct Detection at LHC

In this section, we turn to the direct production of the CSDM pair at the LHC. To calculate the numbers of events of relevant signals and their SM backgrounds, we use FeynRules [40] to generate model files prepared for MadGraph5 [41] that includes Pythia 6 [42] for parton showering & hadronization, and Delphes 3 [43] for fast detector simulation. The leading-order events are obtained in terms of MadGraph5 by extracting samples from the CSDM parameter space in Fig. 1.

From the Higgs portal in (2), the η pair production at the LHC is similar to that of FSDM. The discovery channels mainly include the vector boson fusion (VBF) process

\[ pp \rightarrow jjh^* \rightarrow jj\eta, \quad (14) \]

and the mono-Z process

\[ pp \rightarrow Zh^* \rightarrow Z\eta, \quad (15) \]

where \( h \) is virtual for \( m_\eta > m_h/2 \), and the two jets in (14) can be either the same or different. These processes have been used to derive the prospect of the resonant mass region \( m_\eta \sim m_h/2 \) at the LHC for the FSDM [44–46]. Unlike the FSDM, the main contribution to the production cross sections of these two signal channels at the 14 TeV LHC is dominated by the derivative interactions. Although the derivative interactions enhance the production cross sections, as illustrated in Fig. 6, compared to the SM cross sections of 54 pb, 9.6 pb and 30.9 pb for \( W+jets \), \( Z+jets \) and mono-Z respectively, they are about at least five orders of magnitude smaller. So large gaps between the cross sections make these processes unlikely to constrain the CSDM at the HL-LHC with an integrated luminosity 3000 fb\(^{-1}\). We draw this conclusion based on the 13-TeV CMS cuts reported in [47] and [48] for the VBF and mono-Z respectively.

![Fig. 6 Cross sections of the VBF (left) and mono-Z (right) process at the 14 TeV LHC for the values of \( f \) as in Fig. 1, respectively](image-url)
Fig. 7 The CSDM mass subject to the combination of direct detection (current XENON1T and LZ(2022) [30] limits) as well as the indirect constraints from the Fermi-LAT limits on the DM annihilation cross sections, the Higgs invisible decay and the precision tests on the Higgs couplings, where the conservative ATLAS bound $f > 0.86$ TeV at 95% CL has been taken. The FSDM (the lowest plot) is shown for comparison, where the 5σ discovery limit [46] at the HL-LHC is highlighted in dark green. The references of the other colors are the same as before.
In addition, the contact interactions in (3) provide alternative production processes different from those of FSDM. Among them, the top-loop induced gluon gluon fusion (GGF) process\(^3\)

\[
pp \rightarrow jj\eta\eta, \tag{16}
\]

has the largest signal rate. Besides the GGF process, there are also signal channels with top quark pair such as \(pp \rightarrow \bar{t}t\eta \rightarrow \bar{b}bjj\eta\eta\) with hadronic final states and \(pp \rightarrow \bar{t}t\eta \rightarrow \bar{b}jj\eta\eta\ell\nu\) with leptonic final state(s) [49], whose SM backgrounds are mainly given by \(pp \rightarrow \bar{b}bjjjj\nu\nu\) and \(pp \rightarrow \bar{b}bjj\ell\nu\), respectively. The GGF process has the cross section of order up to \(\sim 10^2\) fb, while the processes with the top quark pairs have cross section of order up to \(\sim 10^{-1}\) fb. Unfortunately, all of these production cross sections are too small. Take the GGF process for example. Compared to its SM background with the cross section of order \(\sim 6 \times 10^4\) pb, the GGF process fails to provide any useful constraint, no matter how the selection of events are performed.

Based on the null results from the VBF, mono-Z and GGF processes, the minimal CSDM with mass \(m_\eta > m_h/2\) is totally invisible at the high-luminosity (HL)-LHC with the integrated luminosity 3000 fb\(^{-1}\). Consider that the CSDM couplings to the SM Higgs and fermions aren’t obviously altered in the situation of non-minimal scenarios, we infer that the small signal rate of CSDM at the LHC in the large DM mass region is probably a general result.

5 Conclusions

In this study we have made a comprehensive investigation on the CSDM, based on the framework of parametrization which can help us estimate the general phenomenological status. Although totally different from the FSDM, the CSDM mimics the FSDM when the scale of global symmetry breaking \(f\) is far than the weak scale. But their differences become “visible” as \(f\) decreases to the order of TeV scale (where the fine tuning is small). The minimal CSDM has been exposed by imposing both direct and indirect constraints. Figure 7 shows how to differentiate it from the FSDM as what follows.

- Disappearing resonant mass region. Due to the derivative interaction the resonant mass region gradually disappears from \(f = \infty\) to \(f = 1\) TeV in Fig. 7.
- Small SI DM-nucleon scattering cross section in certain mass region. Instead of the exclusion mass bound larger than \(\sim 700\) GeV in the FSDM, a large part of the CSDM mass window between \(\sim 67\) GeV and \(\sim 416\) GeV is still beneath the current LZ(2022) limits. Since future XENON1T and LZ experiment can reach a partial of this mass region, they are very useful in distinguishing the CSDM from the FSDM.
- The absence of CSDM at the HL-LHC. Compared to certain signal reach near the resonant region in the FSDM as shown by the dark green curve in Fig. 7, the disappearing resonant mass region together with the small signal rates in the larger DM mass region for the CSDM make the HL-LHC an alternative platform to distinguish these two DM models.

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\(^3\) Concretely speaking, both the contact and Higgs interactions contribute to this GGF process, with the former dominating over the later.
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