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Collider signatures of Higgs-portal scalar dark matter

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ABSTRACT

In the simplest Higgs-portal scalar dark matter model, the dark matter mass has been restricted to be either near the resonant mass ($m_h/2$) or in a large-mass region by the direct detection at LHC Run 1 and LUX. While the large-mass region below roughly 3 TeV can be probed by the future Xenon1T experiment, most of the resonant mass region is beyond the scope of Xenon1T. In this paper, we study the direct detection of such scalar dark matter in the narrow resonant mass region at the 14 TeV LHC and the future 100 TeV hadron collider. We show the luminosities required for the 2σ exclusion and 5σ discovery.

1. Introduction

New physics beyond the Standard Model (SM) has drawn extensive attention since the discovery of the SM Higgs boson [1,2]. While a few problems such as how to stabilize the Higgs mass against ultraviolet radiative corrections are tied to new physics of high mass scale, in this paper we instead focus on dark matter with a mass near the weak scale. In contrast to new physics which appears at a rather high mass scale, such a dark matter model has promising prospect for discovery at both astrophysical and particle collider experiments.

In particular, we are interested in the simplest Higgs-portal dark matter model, in which the dark matter communicates with SM particles via the Higgs scalar. Unlike the fermion dark matter setting, a scalar dark matter in the so-called Higgs-portal scalar dark matter model (HSDM) [3–7] still survives the latest data of direct detections at Xenon100 [8] and LUX [9], indirect detections at Fermi-LAT [10,11], and Higgs invisible decay at the LHC Run 1 [12]. Detailed discussions about this model have been given in the literature [13–42]. Fitting the experimental data indicates that the dark matter mass is either near the resonant mass region between 53 GeV and 62.5 GeV or in a large-mass region above 185 GeV.

While the large-mass region between 185 GeV and 3 TeV can be probed by the future Xenon1T [43], most of the resonant mass region is beyond the reach of this facility. In this paper, we discuss the collider signatures of the scalar dark matter in the HSDM model with a mass between 53 GeV and 62.5 GeV at the 14 TeV LHC and the future 100 TeV proton collider (FCC). We will show that similar to Circular Electron Positron Collider (CEPC) [44,45], FCC will be a useful machine for searching dark matter in this narrow mass region. We will show that for FCC with a luminosity of 10 ab^{-1} the exclusion and discovery sensitivities reach to 57 GeV and 56 GeV respectively through the Vector Boson Fusion (VBF) channel, and 54.8 GeV and 53.9 GeV respectively via the mono-Z channel. It indicates that FCC with 10 ab^{-1} is a competitive facility in comparison with CEPC or Xenon1T.

The remaining parts of the paper are organized as follows. In Sec. 2, we briefly discuss the direct and indirect detection constraints on the HSDM. In Sec. 3 we address the collider phenomenologies for the HSDM with dark matter mass in the narrow resonant mass region at the 14 TeV LHC and the 100 TeV FCC, where we focus on both the VBF channel and mono-Z channel. Our main results are presented in Sec. 4, where we show the luminosities required for the 2σ exclusion and 5σ discovery. Finally we conclude in Sec. 5.

2. Model and constraints

2.1. Model

In the simplest HSDM model, the dark matter s communicates with the SM particles through the SM Higgs scalar. The Lagrangian for this mode reads as

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial s)^2 - \frac{\mu_s^2}{2}s^2 - \frac{\kappa_s}{2}s^2|H|^2 - \frac{\lambda_s}{2}s^4, \qquad (1)$$

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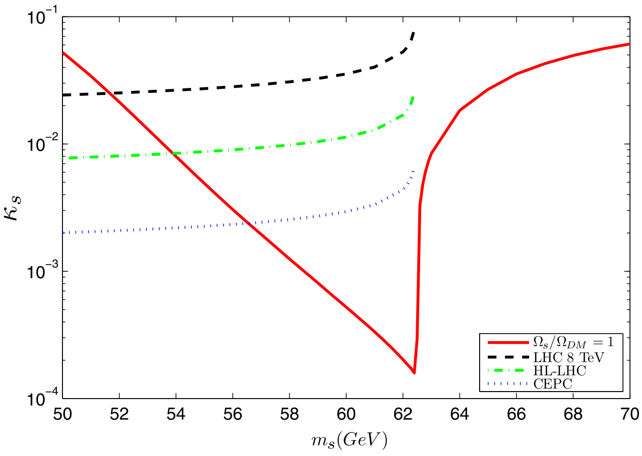

Fig. 1. Indirect constraints on the dark matter mass m_s from the dark matter relic abundance and Higgs invisible decays at the LHC Run 1, HL-LHC and CEPC.

where μ_s, λ_s and κ_s are the singlet scalar bare mass, the self-interaction coupling constant, and the coupling constant between dark matter and SM Higgs, respectively. A Z_2 parity, under which s is odd and other fields are even, is imposed to make the DM stable, which reduces the number of model parameters. After the electroweak symmetry breaking one can obtain

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}(\partial s)^2 - \frac{1}{2}m_s^2 s^2 - \frac{\kappa_s \upsilon}{2}s^2 h - \frac{\kappa_s}{4}s^2 h^2 - \frac{\lambda_s}{2}s^4, \tag{2}$$

where $m_s = \mu_s^2 + \kappa_s \upsilon^2/2$ is the physical mass of the singlet scalar, and $H = (\upsilon + h)/\sqrt{2}$, $s = \langle s \rangle + s$ and $\upsilon \simeq 246$ GeV.

Among the three model parameters, the self-interaction coupling λ_s does not directly affect the DM relic abundance, the DM-nucleon scattering cross section and DM production cross section at colliders, we simply decouple this parameter from the DM phenomenology discussed below. It turns out that the remaining two parameters are strongly constrained.

2.2. Constraints from indirect detections

Assume that the cold dark matter is saturated by the singlet scalar s, s should account for the DM relic density measured by the Planck and WMAP [46],

$$\Omega_{\mathrm{DM}}h^2 = 0.1199 \pm 0.0027, \tag{3}$$

from which one infers the correlation between m_s and κ_s as shown in Fig. 1. Besides the relic abundance in Eq. (3), there are other indirect constraints, including the Higgs invisible decay $h \to ss$ in the mass region $m_s < m_h/2$ and the γ-ray limits from the Fermi-LAT [10,11]. For the Higgs invisible decay, Fig. 1 shows the latest limits at the 8 TeV LHC [12], HL-LHC and CEPC [44], which indicates that m_s below 52 GeV is excluded by the data $\mathrm{Br}(h \to ss) \leq 29\%$, while the HL-LHC and CEPC can reach 54 GeV and 57 GeV, respectively.

2.3. Constraints from direct detections

The direct detection at LUX and Xenon1T can further constrain the parameter space, according to the spin-independent DM-nucleon scattering cross section given by

$$\sigma_{\mathrm{SI}} = \frac{\kappa_s^2 f_N^2 \mu^2 m_N^2}{4\pi m_h^4 m_s^2}, \tag{4}$$

where m_N is the nucleon mass, $\mu = m_s m_N/(m_s + m_N)$ is the DM-nucleon reduced mass, and $f_N \sim 0.3$ is the hadron matrix element [28]. Fig. 2 shows the predicted values of the spin-independent DM-nucleon scattering cross section, together with direct detection limits at XENON100 [8] and LUX [9] experiments. The limits at XENON1T [43] have been also shown. It indicates that the dark matter mass is restricted to a narrow resonant region between 53 GeV and 63 GeV. Once we employ the latest Fermi-LAT limits [33], this narrow mass region is further reduced to a narrow range between 53 GeV and 62.5 GeV.

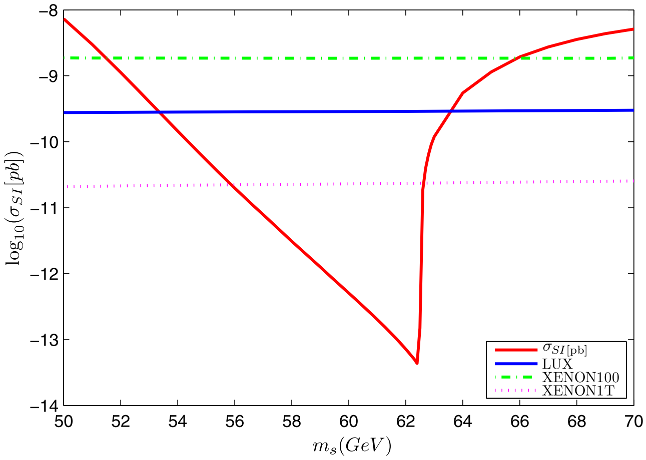

Fig. 2. Direct-detection constraints on dark matter mass m_s from LUX and Xenon experiments. The red curve represents the dark matter relic abundance constraint. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Dark matter at hadron colliders

In this section we study the collider signatures of the scalar dark matter at the 14 TeV LHC and 100 TeV FCC. We will explore the sensitivities at these two colliders for the dark matter mass in the narrow resonant region between 53 GeV and 62.5 GeV. We consider the dominant VBF channel as well as the sub-leading but relatively clean mono-Z channel.

We use FeynRules [47] to generate model files prepared for MadGraph5 [48], which includes Pythia 6 [49] for parton showering and hadronization, and the package Delphes 3 [50] for fast detector simulation. In particular, the default CMS detector card and the Snowmass detector card are used for the 14 TeV and 100 TeV pp collider, respectively. Events are generated by using Madgraph5 at the leading order with the 125 GeV Higgs and fixed value $\kappa_s = 1.0$ for different dark matter masses. Cross sections are reproduced by rescaling κ_s^2 which corresponds to m_s.

3.1. Vector boson fusion

In the VBF channel, the dark matter pairs are produced through the Higgs scalar

$$pp \to h + jj \to ss + jj, \tag{5}$$

where the Higgs h should be on-shell in our case. The primary SM backgrounds to this process include $Z+$jets, $W+$jets, $t\bar{t}+$jets and QCD multi-jets. For simplicity we consider the main contributions arising from $Z+$jets and $W+$jets channels, and adopt the cuts used by the CMS VBF analysis [51] for event selection:

$$\begin{aligned}
&p_{T\,j_{1(2)}} > 50\ \mathrm{GeV}, \quad |\eta_{j_{1(2)}}| < 4.7,\\
&\quad \eta_{j_1}\cdot\eta_{j_2} < 0, \quad \Delta\eta_{jj} > 4.2,\\
&M_{jj} > 1100\ \mathrm{GeV}, \quad \Delta\phi_{jj} < 1.0,\\
&E_T^{\mathrm{miss}} > 130\ \mathrm{GeV},
\end{aligned} \tag{6}$$