Physics Letters B 743 (2015) 228–234

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Heavy WIMP through Higgs portal at the LHC

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ARTICLE INFO

Article history:
Received 3 December 2014
Received in revised form 30 January 2015
Accepted 18 February 2015
Available online 23 February 2015
Editor: J. Hisano

ABSTRACT

The LHC constraints on Higgs-portal WIMPs are studied. Scalar, vector and anti-symmetric tensor fields are considered. They are assumed to be heavier than a half of the Higgs boson mass. We investigate 8 TeV LHC results on signatures of the vector boson fusion, mono-jet and associated production of the Z boson, which proceed via virtual exchange of the Higgs boson. We show that the vector boson fusion channel gives the most stringent constraints on Higgs-portal interactions for all the WIMP models investigated here. The upper limits on vector and tensor Higgs-portal couplings can be 0.43 and 0.16 for the WIMP mass of 65 GeV, respectively. However, they are rapidly weakened for heavier WIMP masses, allowing $\mathcal{O}(1)$ couplings for masses heavier than $\sim$100 GeV. Constraints for scalar WIMPs are very weak. Prospects of the 14 TeV LHC are also discussed. We show that the constraints on the tensor and vector couplings would be improved by a factor of $\sim$1.5–2, depending on the search channels. It would be still challenging to constrain scalar WIMPs.

1. Introduction

Although astrophysical and cosmological evidences have established the existence of the dark matter (DM), its nature has not been demystified (see, e.g., Ref. [1] for a review). In particular, DM interactions with standard model (SM) particles have not been identified except for gravitational ones in spite of enormous experimental efforts. They have been limited by direct or indirect DM searches, for instance, by the LUX experiment [2]. Besides, if the DM has sizable couplings with quarks or gluons, it can be discovered or constrained by collider experiments especially at the LHC [3]. In fact, searching for the DM is one of the main targets for the next phase of the LHC.[1]

The collider searches are qualitatively different from the direct and indirect ones for the DM. The latter particularly depends on the relic abundance of the DM as well as its interactions. For a subcomponent of the DM, the signal strength of direct or indirect searches can be suppressed, even if its coupling is strong. In contrast, signal strengths at colliders depend only on interactions. Weakly-interacting massive particles (WIMPs) are searched, irrespective of whether they are dominant components of the DM. They are assumed to be stable and identified as a missing momentum in detectors.

In this letter, we study LHC signatures of stable WIMPs through the Higgs portal, where they interact with the SM particles only via the Higgs boson [4–6]. They are assumed to be singlet under the SM gauge symmetries. An unbroken Z_2 parity is introduced, where the stability of WIMPs is guaranteed by assigning odd (even) charge to WIMP (SM) particles. We consider scalar, vector and anti-symmetric tensor fields as a candidate of Higgs-portal WIMPs.[2]

Although the Higgs-portal models have been constrained by LHC studies on the Higgs invisible decay, they target WIMPs lighter than a half of the Higgs boson mass [8–17]. In this letter, we study LHC signatures of WIMPs when they are *heavier*. We explore the vector boson fusion (VBF) and Z-boson associated production channels. Besides, WIMPs are produced by gluon fusions via top loops and the intermediate Higgs boson. Such a channel can be identified by using associate productions of a hard jet. Thus, we also investigate the mono-jet signature in light of the current LHC studies [18,19]. It will be shown that the current LHC results constrain the Higgs-portal interactions of the vector and tensor WIMPs to be less than 0.43 and 0.16, respectively, while those for the

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[1] We note that even if the LHC discovers a new particle by, e.g. observing excesses in large missing momentum signatures, it does not immediately imply a discovery of the dark matter particle. We need to investigate carefully that its nature surely satisfies what is expected for the dark matter before such a claim.

[2] The stability of the tensor WIMP may not always require a new Z_2 symmetry [7].

http://dx.doi.org/10.1016/j.physletb.2015.02.042

scalar is very weak. Prospects of the 14 TeV LHC will also be discussed.

The remaining parts of this work are organized as follows. After introducing the Higgs-portal models in Section 2, the relevant LHC signatures and analysis details are described in Section 3. Results for the 8 TeV LHC constraints are shown in Section 4, while Section 5 is devoted to discussions on prospects for the 14 TeV LHC. Finally, our main conclusion are summarized in Section 6.

2. Model

Higgs-portal WIMP models are considered, where WIMP is a scalar, S, vector, V_μ, or anti-symmetric tensor field, $B_{\mu\nu}$.[3] It generally couples to the Higgs boson via a dimension-four interaction operator. The Lagrangian is generally given as

$$\mathcal{L}_S = \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{1}{2}M_S^2 S^2 - \lambda_S S^4 - c_S |H|^2 S^2, \tag{2.1a}$$

$$\mathcal{L}_V = -\frac{1}{4}V^{\mu\nu}V_{\mu\nu} + \frac{1}{2}M_V^2 V^\mu V_\mu - \lambda_V (V^\mu V_\mu)^2 + c_V |H|^2 V^\mu V_\mu, \tag{2.1b}$$

$$\mathcal{L}_B = \frac{1}{4}\partial_\lambda B^{\mu\nu}\partial^\lambda B_{\mu\nu} - \frac{1}{2}\partial^\mu B_{\mu\nu}\partial_\rho B^{\rho\nu} - \frac{1}{4}M_B^2 B^{\mu\nu}B_{\mu\nu} - \lambda_B B_{\mu\nu}B^{\nu\lambda}B_{\lambda\rho}B^{\rho\mu} - c_B |H|^2 B^{\mu\nu}B_{\mu\nu}, \tag{2.1c}$$

where M_χ, λ_χ and c_χ are the mass parameter, quartic self-coupling and interaction strength between the Higgs boson and WIMP, respectively, for $\chi = S, V, B$. In the LHC analysis, c_χ is set to be a real and positive value without loss of generality. Also, $V_{\mu\nu}$ is a field strength of the vector. After the electroweak symmetry is broken, the WIMP mass receives a correction of $\sim c_\chi v^2$. In the analysis, the physical WIMP mass is represented as m_χ. In this letter, we follow Ref. [7] for the tensor model, where a massive anti-symmetric two-form field is analyzed in the transverse representation as a candidate of the DM. In particular, the wave function becomes

$$\langle 0 | B_{\mu\nu} | b(q,\lambda)\rangle = \frac{i}{m_B}\epsilon_{\mu\nu\rho\sigma}\varepsilon^\rho(\lambda) q^\sigma, \tag{2.2}$$

for momentum q and helicity λ.

The invisible decay rate of the Higgs boson with a mass m_H is calculated as

$$\Gamma_S(m_H, m_S; c_S) = \frac{c_S^2}{8\pi}\frac{v^2}{m_H}\sqrt{1-\frac{4m_S^2}{m_H^2}}, \tag{2.3a}$$

$$\Gamma_V(m_H, m_V; c_V) = \frac{c_V^2}{32\pi}\frac{v^2}{m_H}\frac{m_H^4 - 4m_H^2 m_V^2 + 12 m_V^4}{m_V^4}\sqrt{1-\frac{4m_V^2}{m_H^2}}, \tag{2.3b}$$

$$\Gamma_B(m_H, m_B; c_B) = \frac{c_B^2}{4\pi}\frac{v^2}{m_H}\frac{m_H^4 - 4m_H^2 m_B^2 + 6 m_B^4}{m_B^4}\sqrt{1-\frac{4m_B^2}{m_H^2}}, \tag{2.3c}$$

where v is the vacuum expectation value of the Higgs field, $v \simeq 246$ GeV. It is noticed that the vector and tensor productions are enhanced by m_H^4/m_χ^4, if m_H is much larger than m_χ. For the vector final state, this comes from the longitudinal polarization. On the other hand, in the tensor case the wave function (2.2) is proportional to $\varepsilon^\rho q^\sigma / m_B$ but vanishes for $\varepsilon^\rho(\lambda) \propto q^\rho$, leading to the similar scaling behavior in high energy as the vector case. Consequently, the Higgs invisible decay rate becomes large especially for the vector and tensor WIMPs.

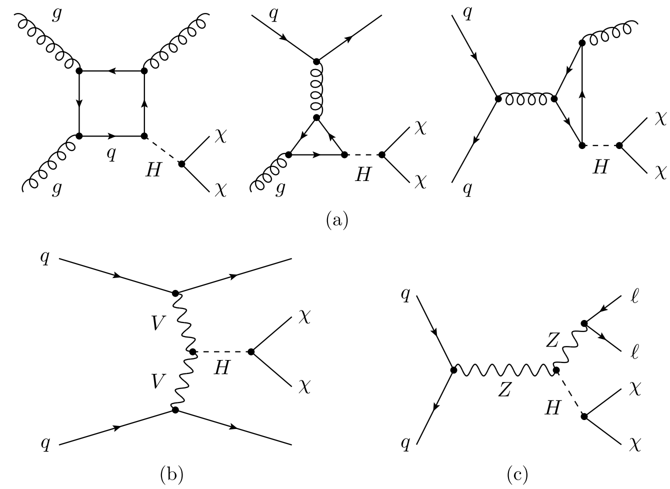

Fig. 1. Representative diagrams for Higgs-portal WIMP-pair production processes in (a) mono-jet, (b) vector-boson fusion, (c) mono-Z production channels.

3. LHC signatures

In this section we discuss LHC signatures for the Higgs-portal models described in the previous section.

Higgs invisible decay signals are definitive probes for the Higgs-portal interactions. ATLAS and CMS collaborations have put limits on the branching fraction of the Higgs invisible decay ($\mathrm{BR_{inv}}$) based on VBF and ZH associated production processes [8,9]. Those constraints can be reinterpreted for bounds on the heavy Higgs-portal WIMP models, where off-shell Higgs bosons intermediate between the SM particles and WIMPs. Besides, new physics searches via mono-jet [19,18], mono-Z [20,21] and mono-W [20,22] signatures can also be a way to investigate Higgs-portal models.

In the following, we explain the details of our VBF, mono-jet and mono-Z analyses for constraints on the heavy Higgs-portal models. On the other hand, since the currently available LHC results for the ZH [8,9] and mono-W [20,22] signatures are based on the template-based analyses (i.e., depending on kinematical distributions of decay products), it is not straightforward to reinterpret them for the constraints on the Higgs-portal models. We do not investigate these channels in this study.

3.1. Vector boson fusion

We briefly explain the analysis details for VBF constraints on the Higgs-portal models. As shown in Fig. 1 WIMP-pair productions are intermediated by the Higgs boson, H^*, as

$$pp \to H^* + jj \to \chi\chi + jj, \tag{3.1}$$

where the Higgs is off-shell when the WIMP is heavier than a half of the Higgs boson mass. Its cross section can be expressed as

$$\sigma_{\chi\chi}(m_\chi, c_\chi) = \int_{4m_\chi^2}^{\infty} \frac{d\tilde{s}}{2\pi}\,\sigma_H(m_{H^*} = \sqrt{\tilde{s}})\frac{2\sqrt{\tilde{s}}}{(\tilde{s}-m_H^2)^2 + \Gamma_H^2 m_H^2} \times \Gamma_\chi(\sqrt{\tilde{s}}, m_\chi; c_\chi), \tag{3.2}$$

where $\tilde{s}$ is the invariant mass squared of the $\chi\chi$ system, and $\Gamma_H = 4.21$ MeV is the total decay width of the Higgs boson at the

[3] It is straightforward to apply the following analysis for a fermion WIMP, which interacts with the Higgs boson by a dimension-five operator.