PROCEEDINGS OF SCIENCE

Simple vector WIMP dark matter

Tomohiro Abe
Institute of Modern Physics and Center for High Energy Physics, Tsinghua University, Beijing 100084, China

Mitsuru Kakizaki
Department of Physics, University of Toyama, Toyama 930-8555, Japan

Shigeki Matsumoto
Kavli IPMU, TODIAS, University of Tokyo, Kashiwa 277-8583, Japan

Osamu Seto*
Department of Life Science and Technology, Hokkai-Gakuen University, Sapporo 062-8605, Japan

Weakly interacting massive particle (WIMP) is well known to be a good candidate for dark matter, and it is also predicted by many new physics models beyond the standard model at the TeV scale. We found that, if the WIMP is a vector particle (spin one particle) which is associated with some gauge symmetry broken at the TeV scale, the Higgs mass is preferred to be $120-125$ GeV, as indeed has been reported by ATLAS and CMS collaborations at the Large Hadron Collider experiment. We present a vector WIMP model based on non-linear sigma model. This model is testable and strongly constrained by experiments for direct and indirect dark matter detection.

VIII International Workshop on the Dark Side of the Universe,
June 10-15, 2012
Rio de Janeiro, Brazil

*Speaker.

PoS(DSU 2012)050

1. Introduction

There are many compelling evidences for the existence of dark matter in our Universe, and many experimental efforts are presently devoted to detect the dark matter directly and indirectly [1]. Since no dark matter candidate exits in the standard model (SM) of particle physics, various dark matter candidates have been proposed. The weakly interacting massive particle (WIMP), whose mass is postulated to be $10-1000$ GeV, is very attractive as a dark matter candidate, because its naturally expected abundance is close to that observed today [2]. Within the framework of new physics beyond the SM, sneutrino with spin 0 and neutralino with spin $1/2$ in supersymmetric models with R-parity, the first Kaluza-Klein (KK) B boson with spin 1 in the universal extra dimension model with KK parity [3], and the heavy photon with spin 1 in little Higgs models with T-parity [4] are such WIMP candidates.

Here, we focus on the vector (spin 1) WIMP. Vector WIMP models in the class of Higgs-portal dark matter, where couplings between the Higgs boson and vector dark matter are adjustable, have been investigated [5]. In this article, we consider the vector WIMP that acquires its mass from the gauge symmetry break down at the TeV scale and has interactions given by the SM gauge coupling [6] .

We construct a simple model of the vector WIMP dark matter based on $SU(2)_L \times U(1)_1 \times U(1)_2$ gauge symmetry. The imposed Z_2 symmetry for dark matter particle to be stable is invariance under the exchange of $U(1)_1$ and $U(1)_2$ gauge interactions. The $U(1)_1 \times U(1)_2$ symmetry is assumed to be broken at the TeV scale into the SM gauge interaction of $U(1)_Y$. This means that the dark matter particle is provided as the partner of the hyper-charge gauge boson and its mass originates form the TeV scale symmetry breaking. Then, the strength of the coupling between two Higgs bosons and two dark matter particles is not a free parameter but definitely given the $U(1)_Y$ gauge coupling. The desired thermal relic density is obtained for the Higgs mass within the range of $120-125$ GeV as reported by ATLAS and CMS collaborations at the Large Hadron Collider (LHC) experiment February 2012 [7]. We also discuss possibility to discover or test the vector WIMP in direct and indirect detection experiments of dark matter.

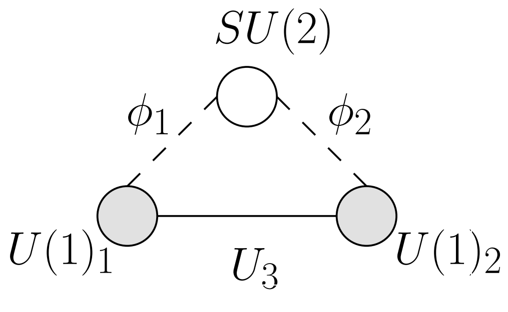

Figure 1: The structure of the $SU(2)_L \times U(1)_1 \times U(1)_2$ model for the vector WIMP dark matter expressed by using the moose notation.

2. Simplest model for the vector WIMP

We consider the simplest model for the vector WIMP dark matter in this section, which is described based on the $SU(2)_L \times U(1)_1 \times U(1)_2$ gauge theory in its electroweak sector. The structure of the gauge-Higgs sector in this model involving symmetries and their breaking patterns is schematically expressed by using the 'moose' notation [8] as shown in Fig.1, where the white circle stands for the SM $SU(2)_L$ gauge symmetry, while black ones are $U(1)$ gauge symmetries ($U(1)_1$ and $U(1)_2$). On the other hand, the solid line represents the non-linear sigma field, $U_3 \equiv \exp(i\pi_3/v_3)$, and broken lines are linear sigma fields, namely, Higgs fields denoted by ϕ_1 and ϕ_2. All of non-linear sigma and Higgs fields spontaneously break the symmetries connected to them into their diagonal ones. In order to guarantee the stability of the vector WIMP, the Z_2 symmetry is imposed by postulating that the model is invariant under the exchange of $U(1)_1$ and $U(1)_2$ gauge interactions, which can be expressed by the symmetry under the left-right reflection of the diagram in Fig.1: $\phi_1 \to \phi_2$, $\phi_2 \to \phi_1$, and $U_3 \to U_3^*$. Both gauge couplings of $U(1)_1$ and $U(1)_2$ interactions as well as vacuum expectation values (VEVs) of two Higgs fields ϕ_1 and ϕ_2 are therefore taking the same value.

There are five Z_2 odd particles: a linear combinations of the $U(1)$ gauge field

$$V_\mu \equiv \frac{B_\mu^{(1)} - B_\mu^{(2)}}{\sqrt{2}} \tag{2.1}$$

with $B_\mu^{(i)}$ being $U(1)_i$ gauge fields, which is nothing but the vector WIMP, the other four scalars from Higgs sector. Those scalars whose masses are obtained from the scalar potential could be heavy enough compared to the vector WIMP. We therefore consider the vector WIMP and other Z_2 even particles only in following discussions. The $U(1)_Y$ gauge boson is given by

$$B_\mu \equiv \frac{B_\mu^{(1)} + B_\mu^{(2)}}{\sqrt{2}}. \tag{2.2}$$

Under this Z_2 symmetric VEV $v \equiv \sqrt{2}v_1 = \sqrt{2}v_2$ and gauge coupling $g' \equiv g'_1/\sqrt{2} = g'_2/\sqrt{2}$ we obtain W and Z boson. With the use of the Weinberg angle θ_W and the Z boson mass m_Z, the mass of the vector WIMP dark matter is expressed by

$$m_{\rm DM} \equiv m_Z \sin\theta_W \sqrt{1 + Y_3^2 v_3^2/v^2} \simeq 178 \text{ GeV}(Y_2 v_3/1 \text{ TeV}), \tag{2.3}$$

where v_3 is the VEV of U_3. It can be seen that the mass of the vector WIMP dark matter is $\mathcal{O}(100)$ GeV when the breaking scale associated with $U(1)_1 \times U(1)_2 \to U(1)_Y$ is the TeV scale.

Interactions between Higgs boson and vector WIMP dark matter are given as

$$\mathcal{L}_{int} = \frac{g'^2}{8} V_\mu V^\mu h^2 + \frac{g'^2 v}{4} V_\mu V^\mu h + \cdots, \tag{2.4}$$

where $h \equiv (h_1 + h_2)/\sqrt{2}$ is identified with the SM-like Higgs boson, by the gauge coupling of the SM $U(1)_Y$ interaction.

3. Vector WIMP predictions

As we have emphasized, in our model, relevant coupling constants are given by the SM gauge coupling. We show the prediction of the vector WIMP on the mass of the Higgs boson, derived from the thermal relic abundance, prospects of the vector WIMP at both direct and indirect detection experiments. In calculation, we have used `micrOMEGAs` [10] after implementing our model into the code. Appropriate modifications are made by using `LanHEP` [11].

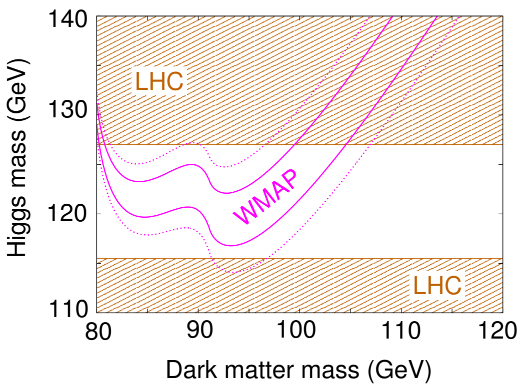

Figure 2: Parameter region consistent with the WMAP observation at 68% (solid line) and 95% (dotted line) C.L. The regions constrained by Higgs searches at the LHC experiment (February 2012) are also shown as shaded ones.

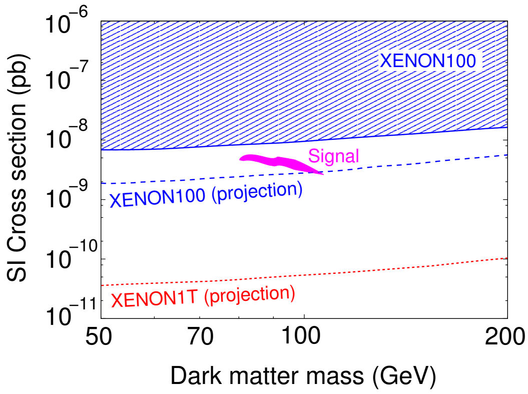

Figure 3: Scattering cross section between the vector WIMP and a proton. Higgs mass is chosen so that it satisfies WMAP and LHC bounds (95%C.L.). The bound (2011) and expected sensitivity (2012) from the XENON experiment are also shown.

3.1 Thermal relic abundance

The thermal relic abundance of the vector WIMP dark matter is obtained numerically by integrating the Boltzmann equation which describes the number density of the dark matter particle in the early universe [9]. Since the vector WIMP annihilates into W and Z boson pairs through the s-channel exchange of the Higgs boson and the vertex is given by g' as in (2.4), the annihilation cross section depends only on the masses of vector WIMP and Higgs boson.

Fig.2 shows the dark matter abundance in the parameter region where the WMAP consistent abundance at 68% (solid line) and 95% (dotted line) C.L. is realized. We have also shown regions which are constrained by current Higgs searches at the LHC experiment as shaded ones. It can be seen from the figure that the Higgs mass is predicted to be $120-125$ GeV, which is very consistent with that strongly suggested by the Higgs searches. It is also worth noting that, if the vector WIMP mass is less than 100 GeV, the abundance is not sensitive to the mass and the Higgs mass favored by the WMAP observation keeps staying around $m_h \simeq 120-125$ GeV.

Note that in fact around $m_{DM} = m_h/2$ there are also regions consistent with the WMAP and LHC bounds due to the rapid annihilation through the resonance.

3.2 Direct detection

We next consider the signal of the vector WIMP at direct detection experiments of dark matter.

The scattering between the dark matter and a nucleon (proton) occurs by exchanging the Higgs boson. Since the $h-V-V$ vertex is fixed by the $U(1)_Y$ gauge coupling, the cross section depends only on $m_{\rm DM}$ and m_h as in the case of the relic abundance.

Result of the scattering cross section is shown in Fig. 3. According to the recent result of the lattice simulation [13] and of chiral perturbation theory [14], we set the π-nucleon sigma term to be $\sigma_{\pi N} = 55$ MeV, which gives conservative results of dark matter signals. The bound released at 2011 (solid line) and expected sensitivity at 2012 (dashed line) from the XENON100 experiment [15] are also shown.

3.3 Indirect detections

We consider the signal of the vector WIMP at indirect detection experiments of dark matter. The vector WIMP has the mass of about 100 GeV and annihilation cross section of $\mathscr{O}(10^{-26})$ cm^3/s mainly into W and Z boson pairs.

We find that the model satisfies the constraint obtained by the Fermi-large area telescope (LAT) experiment observing gamma-rays from milky-way satellites [16] as well as by the PAMELA experiment observing the anti-proton ($\bar{p}$) flux in the cosmic-ray [17] with taking astrophysical uncertainty into account [18]. The future observation by AMS-02 experiment [19] is capable of detecting anti-proton from the vector WIMP.

4. Concluding remark

We have constructed a simple non-linear sigma model in which the vector WIMP is stabilized by the Z_2 parity corresponding to the exchange of two $U(1)$ sectors and has its interactions controlled by only the $U(1)_Y$ gauge coupling constant. The Higgs mass is shown to be generically in the range $120-125$ GeV in scenarios where a neutral vector WIMP that is a partner of the standard model hypercharge gauge boson accounts for the observed dark matter abundance. We would call the coincidence the "vector WIMP miracle". We have shown that the model is testable by current experiments for direct and indirect dark matter detection.

After our paper [6] had been published, the XENON100 result based on 225 live days data was announced July 2012 [20]. In fact, if we take its face value, this vector WIMP model, in particular its "vector WIMP miracle" region, seems to confront the data, although one may remind the possible local dark matter density uncertainty. On the other hand, the resonance region $m_V \simeq m_h/2$ remains consistent. We have assumed that the other Z_2 odd particles are heavy in this work. If vector WIMP coannihilations take place near the pole, the final WIMP abundance is significantly decreased. For such a case, we need careful calculation as in Ref. [21].

Acknowledgments

This work is supported by Grant-in-Aid for Scientific research from the Ministry of Education, Science, Sports, and Culture (MEXT), Japan, (Nos. 22244021 & 23740169 for S.M.), World Premier International Research Center Initiative (WPI Initiative), MEXT, Japan (S.M.), and the scientific research grants from Hokkai-Gakuen (O.S.).

PoS(DSU 2012)050

References

[1] G. Bertone, *Cambridge, UK: Univ. Pr. (2010) 738 p.*

[2] E. Komatsu *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **192**, 18 (2011).

[3] T. Appelquist, H. C. Cheng and B. A. Dobrescu, Phys. Rev. D **64**, 035002 (2001); For a review, D. Hooper and S. Profumo, Phys. Rept. **453**, 29 (2007).

[4] N. Arkani-Hamed, A. G. Cohen and H. Georgi, Phys. Lett. B **513**, 232 (2001); N. Arkani-Hamed, A. G. Cohen, E. Katz, A. E. Nelson, T. Gregoire and J. G. Wacker, JHEP **0208**, 021 (2002); H. C. Cheng and I. Low, JHEP **0309**, 051 (2003); JHEP **0408**, 061 (2004); See also, for a review, M. Perelstein, Prog. Part. Nucl. Phys. **58**, 247 (2007).

[5] A. Djouadi, O. Lebedev, Y. Mambrini and J. Quevillon, Phys. Lett. B **709**, 65 (2012); O. Lebedev, H. M. Lee and Y. Mambrini, Phys. Lett. B **707**, 570 (2012).

[6] T. Abe, M. Kakizaki, S. Matsumoto and O. Seto, Phys. Lett. B **713**, 211 (2012).

[7] ATLAS Collaboration, Phys. Lett. B **710**, 49 (2012); S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **710**, 26 (2012).

[8] H. Georgi, Nucl. Phys. B **266**, 274 (1986).

[9] E. W. Kolb and M. S. Turner, *The Early Universe*, Addison-Wesley (1990); P. Gondolo and G. Gelmini, Nucl. Phys. B **360**, 145 (1991).

[10] G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, Comput. Phys. Commun. **176**, 367 (2007); G. Belanger, F. Boudjema, P. Brun, A. Pukhov, S. Rosier-Lees, P. Salati and A. Semenov, Comput. Phys. Commun. **182**, 842 (2011).

[11] A. Semenov, arXiv:1005.1909 [hep-ph].

[12] See, for a review, G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. **267**, 195 (1996); and, for the vector WIMP, see also J. Hisano, K. Ishiwata, N. Nagata and M. Yamanaka, Prog. Theor. Phys. **126**, 435 (2011).

[13] K. Takeda, S. Aoki, S. Hashimoto, T. Kaneko, J. Noaki and T. Onogi [JLQCD collaboration], Phys. Rev. D **83**, 114506 (2011).

[14] J. M. Alarcon, J. Martin Camalich and J. A. Oller, Phys. Rev. D **85**, 051503 (2012).

[15] E. Aprile *et al.* [XENON100 Collaboration], Phys. Rev. Lett. **107**, 131302 (2011); M. Schumann [XENON100 Collaboration], PoS **IDM2010**, 029 (2011).

[16] M. Ackermann *et al.* [Fermi-LAT collaboration], Phys. Rev. Lett. **107**, 241302 (2011).

[17] O. Adriani *et al.* [PAMELA Collaboration], Phys. Rev. Lett. **105**, 121101 (2010).

[18] C. Evoli, I. Cholis, D. Grasso, L. Maccione and P. Ullio, Phys. Rev. D **85**, 123511 (2012).

[19] `http://www.ams02.org/`.

[20] E. Aprile *et al.* [XENON100 Collaboration], arXiv:1207.5988 [astro-ph.CO].

[21] G. Servant and T. M. P. Tait, Nucl. Phys. B **650**, 391 (2003); M. Kakizaki, S. Matsumoto, Y. Sato and M. Senami, Phys. Rev. D **71**, 123522 (2005); G. Belanger, M. Kakizaki and A. Pukhov, JCAP **1102**, 009 (2011).

PoS(DSU 2012)050