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Indirect signature of dark matter with the diphoton resonance at 750 GeV

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Motivated by the recently reported diphoton resonance at 750 GeV, we study a new axion-like bosonic portal model of dark matter physics. When the resonance particle is identified as the pseudo-scalar mediator, via which the standard model sector would interact with the dark matter sector, the data from collider physics would provide profound implications to dark matter phenomenology. In this paper, we first identify the preferred parameter space of the suggested portal model from the results of the LHC run with $\sqrt{s} = 13$ TeV, and then we examine the dark matter signature taking into account the data from cosmic-ray experiments including Fermi-LAT dwarf galaxy γ-ray search, HESS γ-line search, and future CTA diffuse γ-ray and γ-line searches.

1. Introduction

The ATLAS [1] and CMS [2] Collaborations reported a new resonance at around 750 GeV in the diphoton channel seen in the first data obtained at the $\sqrt{s} = 13$ TeV LHC run in December 2015. In March 2016, the results were updated with more data and new analysis with different assumptions on the width and spin state of the resonance particle [3,4]. Interestingly, the claimed local significance stays high or even slightly grows from $3.9\sigma/2.6\sigma$ (ATLAS with 45 GeV decay width/CMS, December 2015) to $3.9\sigma/2.9\sigma$ (ATLAS/CMS with 13 TeV data, March 2016). When (8 + 13 TeV) data are considered by CMS the significance becomes 3.4σ. The global significance is still low ($\lesssim 2\sigma$) for both experiments when the look-elsewhere effect is taken into account. The ATLAS result shows a slightly better fit to the data with a largish width $\Gamma/M \approx 6\%$ than with a narrow width $\Gamma/M \ll 1\%$ but the CMS result is consistent with narrow width approximation so that the result is not conclusive yet. The resonance signals do not seem accompanied by significant missing energy, leptons or jets. The situation resembles the situation in 2011–2012 when the excess in diphoton channel was announced in the Higgs boson search.

Since we also have observed that several $2\sigma \sim 3\sigma$ 'excesses' disappeared as statistical fluctuations in the past, we are extremely cautious in taking these observations as a signal of new physics beyond the standard model. However, we think that the following points make the observation more interesting and many authors immediately suggested their interpretations:

- Both the ATLAS and CMS Collaborations reported the excess with $>2\sigma$ significance, which is rather exceptional.[1] Even more interestingly, the significance grows with more data, which would strengthen our confidence.
- The locations of the reported excess are well within the experimental uncertainties: $M_{\rm ATLAS} \approx 750$ GeV and $M_{\rm CMS} \approx 760$ GeV. We take 750 GeV as a representative value in our analysis below.
- The excesses locate a bit far from the end points of the data from both experiments.
- The excesses consist of 3–5 successive bins in the data from both experiments.

Instead simply adding additional way of interpretation, we want to discuss a bit different phenomenological aspect of the current observation by connecting dark matter problem in this

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[1] Indeed, the current situation is similar to the one when the announcement of the Higgs signature was made late 2011 with similar statistical significances from both experiments [5,6].

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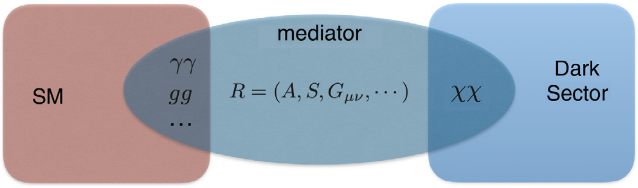

Fig. 1. The schematic diagram of the standard model (SM)-bosonic mediator (Mediator)—dark sector. The bosonic mediator can be a scalar (S), pseudo-scalar or axion (A), and spin-2 mediator ('graviton', G) with the mass of 750 GeV.

paper. We consider new portal interactions between the dark matter sector and the standard model sector through the observed resonance state as the mediator. See Fig. 1 which depicts the schematic diagram showing how the two sectors are linked via new portal interactions through scalar (S), pseudo-scalar (A) or tensor (G), which may be identified with the observed resonance at 750 GeV.[2] We note that the most interesting case for dark matter indirect detection is found with the pseudo-scalar mediator, A, since other cases with S and G are all suppressed by the small velocity as $v^2 \ll 1$ in current universe. Thus, we will focus on the pseudo-scalar case in below and examine the details of indirect detection of the dark matter signature in cosmic-ray.

The content of the paper consists as follows. In the next section, we will define our setup to discuss the 750 GeV mediator, and discuss collider signature and bounds from the LHC run-1 with $\sqrt{s} = 8$ TeV as well as the new data with $\sqrt{s} = 13$ TeV in the following section. We examine the preferred parameter space from the collider physics data and found the potential detection of the indirect signature of dark matter in Section 3 then conclude in Section 4.

2. A Pseudo-scalar portal

An intriguing possibility is that dark matter would communicate with the visible sector of the standard model (SM) via a 'portal'. In literature, various portals have been suggested: the Higgs portal ($\sim |H|^2 \mathcal{O}_b$) and the neutrino portal via Yukawa interactions ($\sim \bar{\ell} H \mathcal{O}_f$), where $\mathcal{O}_b$ and $\mathcal{O}_f$ are bosonic and fermionic singlet operators of the dark sector, respectively. In principle, however, the dark sector gauge symmetry structure can be extensively involved and may play a role to make the dark matter stable. [21]

Here we take the resonance is nothing but the mediator between the standard model sector and the dark sector where dark matter belongs to. The resonance, located at 750 GeV, is bosonic with $s = 0$ or 2. Because of Landau-Yang theorem (or Furry's theorem) [22], a massive vector mediator is excluded. The singlet pseudo-scalar A interacts with the SM gauge bosons as well as a Dirac fermion dark matter χ, described by the following effective Lagrangian,

$$\mathcal{L}_A = -\frac{A}{\Lambda}\left(a_1 F^{Y}_{\mu\nu}\tilde{F}^{Y\mu\nu} + a_2 W_{\mu\nu}\tilde{W}^{\mu\nu} + a_3 G_{\mu\nu}\tilde{G}^{\mu\nu}\right) - i\lambda_\chi A\,\bar{\chi}\gamma^5\chi\,, \quad (1)$$

where the dual field strength tensor is $\tilde{F}_{\mu\nu} \equiv \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$, etc. For more generic Lagrangian with generic spin (i.e. $s = 0, 1, 2$) and CP-states which couple to dibosons, see e.g. Ref. [23].

In this model, the pseudo-scalar can be produced via gluon fusion at the LHC, decaying into a pair of SM gauge bosons.[3] When the pseudo-scalar decays substantially into $\gamma\gamma$ compared to $WW/ZZ/Z\gamma$, it can explain the diphoton excess recently reported. If $m_A > 2m_\chi$, the pseudo-scalar can also decay into a pair of dark matter leading to a signal with a large missing energy. This may help to understand a largish decay width $\Gamma/M \simeq 6\%$ as pointed out in Refs. [7–9,15] even though a narrow width is also allowed.

The similar pseudo-scalar resonance can play a role of mediator between the SM and dark matter sectors [25,26]. The DM annihilation cross sections into gauge bosons are given by

$$\langle \sigma v_{\rm rel}\rangle_{\gamma\gamma} = \frac{\lambda_\chi^2 a_{\gamma\gamma}^2}{4\pi\Lambda^2}\frac{16m_\chi^4}{(4m_\chi^2 - m_A^2)^2 + \Gamma_A^2 m_A^2} + \mathcal{O}(v_{\rm rel}^2), \quad (2)$$

$$\langle \sigma v_{\rm rel}\rangle_{Z\gamma} = \frac{\lambda_\chi^2 a_{Z\gamma}^2}{8\pi\Lambda^2}\frac{16m_\chi^4}{(4m_\chi^2 - m_A^2)^2 + \Gamma_A^2 m_A^2}\left(1 - \frac{m_Z^2}{4m_\chi^2}\right)^3 + \mathcal{O}(v_{\rm rel}^2), \quad (3)$$

$$\langle \sigma v_{\rm rel}\rangle_{ZZ} = \frac{\lambda_\chi^2 a_{ZZ}^2}{4\pi\Lambda^2}\frac{16m_\chi^4}{(4m_\chi^2 - m_A^2)^2 + \Gamma_A^2 m_A^2}\left(1 - \frac{m_Z^2}{m_\chi^2}\right)^{3/2} + \mathcal{O}(v_{\rm rel}^2), \quad (4)$$

$$\langle \sigma v_{\rm rel}\rangle_{WW} = \frac{\lambda_\chi^2 a_{WW}^2}{8\pi\Lambda^2}\frac{16m_\chi^4}{(4m_\chi^2 - m_A^2)^2 + \Gamma_A^2 m_A^2}\left(1 - \frac{m_W^2}{m_\chi^2}\right)^{3/2} + \mathcal{O}(v_{\rm rel}^2), \quad (5)$$

$$\langle \sigma v_{\rm rel}\rangle_{gg} = \frac{2\lambda_\chi^2 a_{gg}^2}{\pi\Lambda^2}\frac{16m_\chi^4}{(4m_\chi^2 - m_A^2)^2 + \Gamma_A^2 m_A^2} + \mathcal{O}(v_{\rm rel}^2), \quad (6)$$

where

$$a_{\gamma\gamma} = a_1\cos^2\theta_W + a_2\sin^2\theta_W, \quad (7)$$

$$a_{Z\gamma} = (a_2 - a_1)\sin(2\theta_W), \quad (8)$$

$$a_{ZZ} = a_1\sin^2\theta_W + a_2\cos^2\theta_W, \quad (9)$$

$$a_{WW} = 2a_2, \quad (10)$$

$$a_{gg} = a_3\,. \quad (11)$$

We note that all the gauge boson channels are s-wave. Here, the partial decay rates of the pseudo-scalar are

$$\Gamma_A(\gamma\gamma) = \frac{m_A^3}{4\pi\Lambda^2}a_{\gamma\gamma}^2, \quad (12)$$

$$\Gamma_A(Z\gamma) = \frac{m_A^3}{8\pi\Lambda^2}a_{Z\gamma}^2\left(1 - \frac{m_Z^2}{m_A^2}\right)^3, \quad (13)$$

$$\Gamma_A(ZZ) = \frac{m_A^3}{4\pi\Lambda^2}a_{ZZ}^2\left(1 - \frac{4m_Z^2}{m_A^2}\right)^{\frac{3}{2}}, \quad (14)$$

$$\Gamma_A(WW) = \frac{m_A^3}{8\pi\Lambda^2}a_{WW}^2\left(1 - \frac{4m_W^2}{m_A^2}\right)^{\frac{3}{2}}, \quad (15)$$

$$\Gamma_A(gg) = \frac{2m_A^3}{\pi\Lambda^2}a_{gg}^2, \quad (16)$$

$$\Gamma_A(\bar{\chi}\chi) = \frac{\lambda_\chi^2 m_A}{8\pi}\left(1 - \frac{4m_\chi^2}{m_A^2}\right)^{\frac{3}{2}}\theta\left(\frac{m_A}{2m_\chi} - 1\right). \quad (17)$$

For $m_\chi > m_A$, dark matter can annihilate into a pair of pseudo-scalars with the annihilation cross section given by

$$\langle \sigma v_{\rm rel}\rangle_{AA} = \frac{\lambda_\chi^4}{24\pi}\frac{m_\chi^6}{(m_a^2 - 2m_\chi^2)^4}\left(1 - \frac{m_A^2}{m_\chi^2}\right)^{5/2} v_{\rm rel}^2\,. \quad (18)$$

[2] While we were finishing our paper, we noticed some papers appeared on arXiv with different but related approaches to dark matter physics [7–14]. We also see more recent works [15–20] in a related direction.

[3] See Ref. [24] for various constraints on pseudo-scalars coupled to two photons and gluons.