The 750 GeV Diphoton Excess from a Pseudoscalar in Fermionic Dark Matter Scenario

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Abstract

Assuming that the newly announced 750 GeV diphoton excess by ATLAS and CMS is due to a decaying pseudoscalar particle, we analyze the singlet fermionic dark matter scenario with the pseudoscalar playing the role of the mediator. The dark sector connects to the standard model sector through the Higgs portal and effective operators of gluons and photons. We show that there is a range of dark matter masses within $\sim 88-280$ GeV that beside giving the correct relic density provided by Planck, matches also with the total decay width of $25-45$ GeV measured by ATLAS. Due to the presence of the pseudoscalar mediator, the DM-nucleon cross section is velocity suppressed so that the model evades easily the bounds put by even future direct detection experiments such as XENON1T.

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1 Introduction

Recently in the early LHC Run 2 data with center-of-mass energy 13 TeV, an excess in the diphoton events with the invariant mass of about 750 GeV has been announced by ATLAS and CMS [1, 2] with local significances of 3.6σ in ATLAS and 2.6σ in CMS. If this is not just a statistical fluctuation then the first hint into the beyond the standard model (BSM) has been found [3]. The new particle could be a spin-even field i.e. a spin 0 or a spin 2 (graviton) according to the Landau-Yang theorem. The simplest scenario will be the case of a scalar or a pseudoscalar decaying into two photons [4, 5, 6, 7]. The decay width reported by ATLAS for the resonance is in the range $25 - 45$ GeV. Such a large decay width can not be obtained by decaying the new particle into only SM particles which gives a width of the order of MeV. One possibility is the existence of some additional particles that can accommodate in the dark matter scenarios. See [8, 9, 10, 11, 12, 13] for some of the DM models incorporating the scalars as a DM condidate or a mediator. In models with scalar then the observed 750 GeV excess would play the role of a (pseudo)scalar mediator between the dark sector and the DM sector. The models with (pseudo)scalars mediators (see e.g. [14, 15, 16, 17]) can in principle be capable of explaining the 750 GeV diphoton excess [18, 19, 20, 21, 22, 23].

In this paper we investigate the case where the new resonance is a pseudoscalar and the dark matter candidate is a singlet Dirac fermion (see [24, 25, 26] for examples on fermionic DM). The pseudoscalar here interacts with the SM particles through two portals; via the Higgs portal that leads to the mixing of the SM Higgs and the pseudoscalar, and through the effective operators which let the pseudo-scalar interacts effectively with the gluons and the photon. The interesting result is that the model suggests a range of dark matter masses which fulfill the observed relic abundance of $\Omega_{\rm DM} h \sim 0.12$ and the decay width of around $25 - 45$ GeV. This is in contrast with some statements in the literature [27] where have claimed that pseudoscalar mediator may lead to inconsistency in indirect detection bounds and the observed decay width. Although the annihilation cross section with a pseudoscalar mediator is not velocity suppressed but the mixing angle can take care of reducing that and make a balance between the annihilation cross section and branching ratio. We therefore emphasize on the importance of the Higgs portal having a 750 GeV pseudoscalar decaying into two photons. The advantage of a pseudoscalar mediator is that the DM-nucleon elastic scattering cross section is velocity suppressed and the model evades the constraint from direct detection experiments like LUX and XENON100 or even XENON1T.

The paper is written with the following parts. In section 2 we introduce the dark matter model with pseudoscalar mediator. Then in section 3 we present the necessary decay width we use in our analyses. In section 4 we show that dark matter masses outside the resonance range ~ 300 is consistence with the decay width of $25 - 45$ GeV. We conclude the paper in section 5.

2 Pseudoscalar Mediator

We assume that the observed diphoton resonance at 750 GeV is coming from a pseudoscalar particle. Motivated by the fact that the total decay width obtained by ATLAS is much larger than the decay width into only standard model particles, we consider a singlet Dirac fermion to which the pseudoscalar has the chance to decay. The pseudoscalar itself plays the role of a mediator between the dark sector and the SM sector. We suppose that the pseudoscalar field couples to the SM through the Higgs portal and through effective operators being coupled to the gluons and photons with dimensionful couplings at some scale Λ. The dark sector lagrangian for such a setting reads,

$$\mathcal{L}_{\rm Dark} = \bar{\chi}(i\partial\!\!\!/ - m_{\rm DM})\chi + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{m^2}{2}\phi^2 - \frac{\lambda_\phi}{4}\phi^4\,, \tag{1}$$

where ϕ stands for the pseudoscalar and χ is the singlet Dirac fermion representing the Dark matter candidate. The lagrangian for the interactions is given by,

$$\mathcal{L}_{\rm int} = -ig_\chi\phi\bar{\chi}\gamma^5\chi - g_H\phi^2 H^\dagger H + \frac{\lambda_G}{\Lambda}\phi G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{\lambda_\gamma}{\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}\,, \tag{2}$$

where $G_{\mu\nu}$ and $F_{\mu\nu}$ are the colored $SU(3)_c$ and electromagnetic $U(1)$ field strengths in the SM respectively, and Λ is a new physics scale to be taken here $\Lambda = 10$ TeV. The tilde denotes the dual of the strength field, e.g. $\tilde{G}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}G_{\rho\sigma}$. Having in mind that ϕ, $\bar{\chi}\gamma^5\chi$, $\tilde{G}^{\mu\nu}$ and $\tilde{F}^{\mu\nu}$ are odd under CP transformation and H, $G^{\mu\nu}$ and $F^{\mu\nu}$ are CP even, both the lagrangians (1) and (2) are CP invariant. The Higgs potential in the SM sector is,

$$V = -\mu H^\dagger H - \lambda_H\left(H^\dagger H\right)^2. \tag{3}$$

Note that we have not included the interactions terms such as $\phi W_{\mu\nu}\tilde{W}^{\mu\nu}$ and $\phi B_{\mu\nu}\tilde{B}^{\mu\nu}$ in the lagrangian (2), instead implicitly we can have the pseudoscalar-gauge boson couplings through the mixing of pseudoscalar and Higgs together with the Higgs-gauge boson interactions in the SM. The presence of the term $\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$ in the lagrangian (2) enhances the branching ratio of the pseudoscalar decaying into two photons. The vacuum expectation value of the pseudoscalar is taken to be non-zero, $\langle\phi\rangle = v_\phi$. For the Higgs particle the LHC has fixed the mass being $m_H \sim 125$ GeV and the Higgs vacuum expectation value is knwon to be $v_H = 246$ GeV. Having chosen a non-zero *vev* for the pseudoscalar there is a mixing between the Higgs and the pseudoscalar. Assuming that $\phi = v_\phi + \rho'$ and $H^\dagger = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & v_H + h' \end{pmatrix}$, after diagonalizing the mass matrix, the mass eigenvalues (eigenstates) are described in terms of the Higgs mass (field) and pseudoscalar mass (field) and a mixing angle $\sin\theta$. The mixing therefore opens a channel through which the pseudoscalar can decay into SM particles. Denoting the Higgs and pseudoscalar mass eigenstates by h and ρ respectively, the mass eigenvalues are given as the following,

$$\begin{aligned} m_h^2 &= \frac{m_{h'}^2 + m_{\rho'}^2}{2} + \frac{m_{h'}^2 - m_{\rho'}^2}{2}\sqrt{1+y^2} \\ m_\rho^2 &= \frac{m_{h'}^2 + m_{\rho'}^2}{2} - \frac{m_{h'}^2 - m_{\rho'}^2}{2}\sqrt{1+y^2}\,, \end{aligned} \tag{4}$$

where

$$y = \frac{2m_{h'\rho'}^2}{m_{h'}^2 - m_{\rho'}^2}, \qquad m_{h'\rho'}^2 = 2g_H v_H v_\phi, \qquad m_{h'}^2 = 2\lambda_H v_H^2, \qquad m_{\rho'}^2 = 2\lambda_\phi v_\phi^2. \tag{5}$$

The mass eigenvalues now are taken to be the Higgs and the mass of the new resonance, i.e. $m_h \equiv m_H \sim 125$ GeV and $m_\rho \sim 750$ GeV respectively. The stability conditions put already some constraints on the couplings of the model which are $\lambda_\phi > 0$, λ_H and $\lambda_\phi \lambda_H > g_H > 0$ (for more details see [28]).

3 Partial Decay Widths

Due to mixing with the SM Higgs, the pseudoscalar decay channels incorporate all that of the SM Higgs, multiplied by a factor depending on the mixing angle. Within the SM without DM sector therefore, we have for its total decay width, $\Gamma^{\rm tot} = \sin^2\theta\ \Gamma^{\rm SM}_{\rm Higgs}$. Given the measured value of the Higgs decay width, $\Gamma^{\rm SM}_{\rm Higgs} \sim 4$ MeV, the total decay width of the pseudoscalar will be quite reduced for a reasonably small value of the mixing angle. In order for the pseudoscalar to be the one responsible for the observed 750 GeV diphoton excess, its total decay width needs to get quite enhanced by contributions from physics beyond the SM. In the model outlined above, there is one new decay channel ($\rho \to \chi\chi$) and two modified decay rate ($\rho \to \gamma\gamma, gg$) for the pseudoscalar. In the viable parameter space where $m_{\rm DM} < m_\rho/2$, the total decay width is increased by the following invisible decay width

$$\Gamma_\chi = \Gamma(\rho \to \bar\chi\chi) = \frac{g_\chi^2 m_\rho \cos^2\theta}{8\pi}(1 - \frac{4m_{\rm DM}^2}{m_\rho^2})^{1/2}. \tag{6}$$

The pseudoscalar decay into two photons is induced predominantly via W boson and heavy fermions, in particular the top quark. The relevant decay rate is modified by the

New Physics (NP) effects through the dimension five effective operator. The resulting decay rate is

$$\Gamma_\gamma = \Gamma(\rho \to \gamma\gamma) = (\frac{\alpha_{\rm em}}{4\pi})^2 \frac{m_\rho^3}{16\pi v_H^2}|\mathcal{F}|^2\,, \tag{7}$$

where

$$\mathcal{F} = \mathcal{F}_W(\beta_W) + \sum_f N_c Q_f^2 \mathcal{F}_f(\beta_f)\sin\theta + \frac{16\pi v_H}{\alpha_{\rm em}}\frac{\lambda_\gamma}{\Lambda}\cos\theta \tag{8}$$

and $\beta_x = \frac{4m_x^2}{m_\rho^2}$.

The loop functions read

$$\begin{aligned} \mathcal{F}_W(\beta) &= 2 + 3\beta = 3\beta(2-\beta)f(\beta) \\ \mathcal{F}_f(\beta) &= -2\beta\Big(1 + (1-\beta)f(\beta)\Big) \\ f(\beta) &= -\frac{1}{4}\Big(\log(\frac{1-\sqrt{1+\beta}}{1-\sqrt{1-\beta}}) + i\pi\Big)^2. \end{aligned} \tag{9}$$

The pseudoscalar decay into two gluons is modified with a contribution from the relevant effective operator. The final result is

$$\Gamma_g = \Gamma(\rho \to gg) = \frac{\alpha_s^2 m_\rho^3}{72\pi^3 v_H^2}|\mathcal{F}|^2\,, \tag{10}$$

where

$$\mathcal{F} = \sum_q \mathcal{F}_q(\beta_q)\sin\theta + (\frac{12\pi v_H}{\alpha_s})\frac{\lambda_g}{\Lambda}\cos\theta \tag{11}$$

and

$$\mathcal{F}_q(\beta) = \frac{3}{2}\beta(1 + (1-\beta)f(\beta)). \tag{12}$$

For some reasonable values of the couplings as $\lambda_\gamma = \lambda_g \sim 0.2$ and the UV scale $\Lambda \sim 10$ TeV, it can be seen that both Γ_γ and Γ_g are mainly exhausted by the contribution from the effective interaction. We also find that $\Gamma_g \sim 2\Gamma_\gamma \sim 0.1$ GeV. It is then expected that Γ_χ can bring the pseudoscalar total decay width into the desired value of ~ 45 GeV. This is in fact the case when for instance, we choose $m_{\rm DM} \sim 10^2$, $g_\chi \sim 1.2$ and $\sin\theta = 0.1$.

4 Relic Abundance and 750 GeV Diphoton Width Constraints

In the present model the new resonance being responsible for the observed diphoton excess is a pseudoscalar and at the same time plays the role of the mediator between SM particles and the DM particle. Having introduced two effective operators of dimension five, the DM annihilation channels are now $\chi\chi \to W^+W^-, ZZ, hh, \bar{f}f, \gamma\gamma, gg$. SM

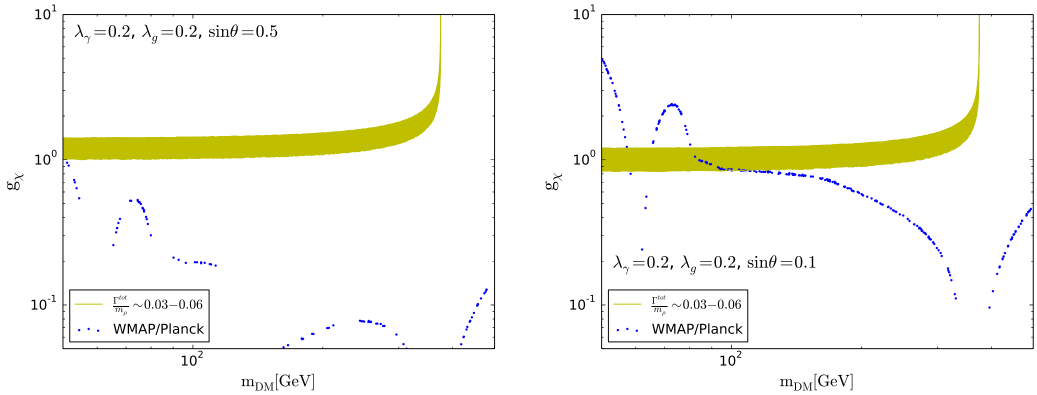

Figure 1: The viable parameter space in the dark sector is shown respecting the WMAP/Planck results. We display the region in the plane $m_{\rm DM} - {\rm g}_\chi$ which satisfies the LHC constraint on the resonance total decay width, i.e., $\Gamma^{\rm tot}/m_\rho \sim 0.03 - 0.06$. The left panel corresponds to a mixing angle as $\sin\theta = 0.5$ and in the right panel $\sin\theta = 0.1$ is chosen. Here we set $\lambda_g = 0.2$ and $\lambda_\gamma = 0.2$.

fermions are denoted by f. One question that we would like to address here is if there can be viable regions in the DM sector which is consistent with the expected resonance of mass ~ 750 GeV and decay width of ~ 45 GeV. We fix the UV scale as $\Lambda = 10$ TeV and perform our computations for two sets of the effective couplings as $\lambda_g = \lambda_\gamma = 0.2$ and $\lambda_g = 3\lambda_\gamma = 0.6$. We pointed out earlier that the resonance decay into a pair of DM, dominants its total decay width. Therefore, the total width is much sensitive to two parameters $m_{\rm DM}$ and g_χ, in particular when $m_{\rm DM} \sim m_\rho/2$. To do the DM phenomenology we implement our model into the program MicrOMEGAs [29]. We then study the dependency of the viable parameter space to the mixing angle, respecting the WMAP and Planck bounds on the relic density [30, 31] and the early LHC-13TeV expected range for the resonance decay width $\Gamma^{\rm tot}/m_\rho \sim 0.03 - 0.06$. Our numerical results for the set $\lambda_g = \lambda_\gamma = 0.2$ are shown in Figs. 1, 2 and 3 for various values of the mixing angle for DM mass in the range 50 GeV up to 500 GeV. It is evident from the figures the role of the mixing angle is quite subtle in finding the DM mass range which gives both the relic density and the resonance decay width correctly. Almost independent of the mixing angle, the correct decay width is obtained for $g_\chi \sim 1$. For quite large mixing angle, i.e., $\sin\theta = 0.5$, there is no DM candidate with $g_\chi \sim 1$ since now the annihilation cross section favors small values of the coupling to give the correct relic density. On the other side, for smaller values of the mixing angle there can always be found a viable DM mass which starts from ~ 80 GeV up to ~ 300 GeV with decreasing the mixing angle. Our findings for the set $\lambda_g = 3\lambda_\gamma = 0.6$ are illustrated in Figs. 4, 4 and 5. It can be seen readily that our results do not change much by increasing λ_g.

Assuming that a resonance underlies the observed excess, the diphoton signal cross section is given by $\sigma_{\gamma\gamma} \sim \sigma({\rm pp} \to \rho){\rm Br}(\rho \to \gamma\gamma)$. To compute the pseudoscalar pro-

$m_{\rm DM}$ [GeV]	g_χ	$\sin\theta$	λ_g	Width [GeV]	$\sigma_{\rm pp\to\rho}$ [pb]	$\sigma_{\rm pp\to\gamma\gamma}$ [fb]
88	0.95	0.1	0.2	$\sim$ 28	$\sim$ 0.663	$\sim$ 1.26
190	1.18	0.05	0.2	$\sim$ 38	$\sim$ 0.667	$\sim$ 0.93
280	1.29	0.005	0.2	$\sim$ 35	$\sim$ 0.669	$\sim$ 1.01
87	0.95	0.1	0.6	$\sim$ 29	$\sim$ 5.97	$\sim$ 10.9
180	1.05	0.05	0.6	$\sim$ 35	$\sim$ 6.01	$\sim$ 9.13
225	1.08	0.005	0.6	$\sim$ 31	$\sim$ 6.02	$\sim$ 10.35

Table 1: The diphoton signal cross section at 13 TeV are summarized for six benchmark points.

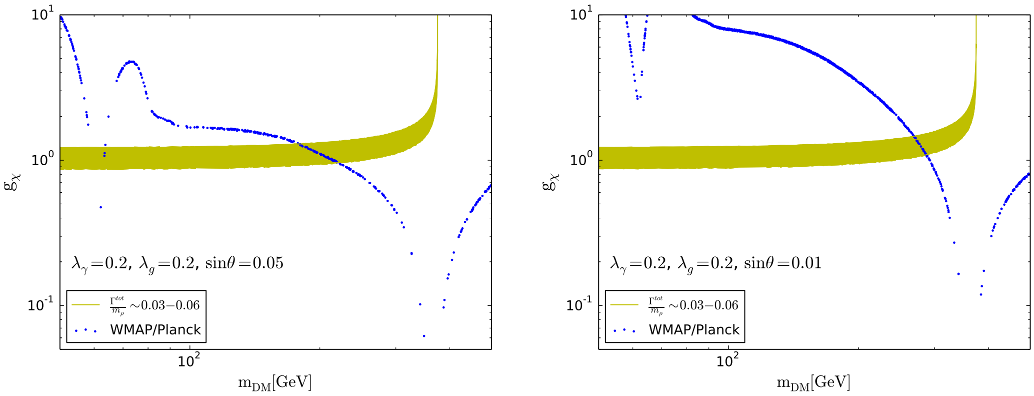

Figure 2: The same as Fig. 1 except that in the left panel $\sin\theta = 0.05$ and in the right panel $\sin\theta = 0.01$ are chosen.

duction cross section we first implement our model into FeynRules [32] and then into MadGraph5 [33]. Since the decay rate of the resonance into diphoton is mainly governed by the effective interaction, we employ the relation $\Gamma_\gamma \sim \frac{m_\rho^3}{\pi}(\frac{\lambda_\gamma}{\Lambda})^2\cos^2\theta$. The numerical predictions for the signal cross section are presented in Table. 1 for six benchmark points, taking two different values for the gloun effective coupling as $\lambda_g = 0.2$ and 0.6. We realize that for $\lambda_g \gtrsim 0.2$ it is possible to explain the diphoton excess for DM masses in the range $\sim 88 - 280$ GeV.

5 Conclusion

The exciting report by ATLAS and CMS [1, 2] on a 750 GeV excess in the diphoton events if not merely a statistical fluctuation will give a first insight towards the beyond the standard model and perhaps a clue in explaining some cosmological challenges like the issue of the dark matter. In this paper we examine a fermionic dark matter candidate that communicate with the standard model by a pseudoscalar through the Higgs portal

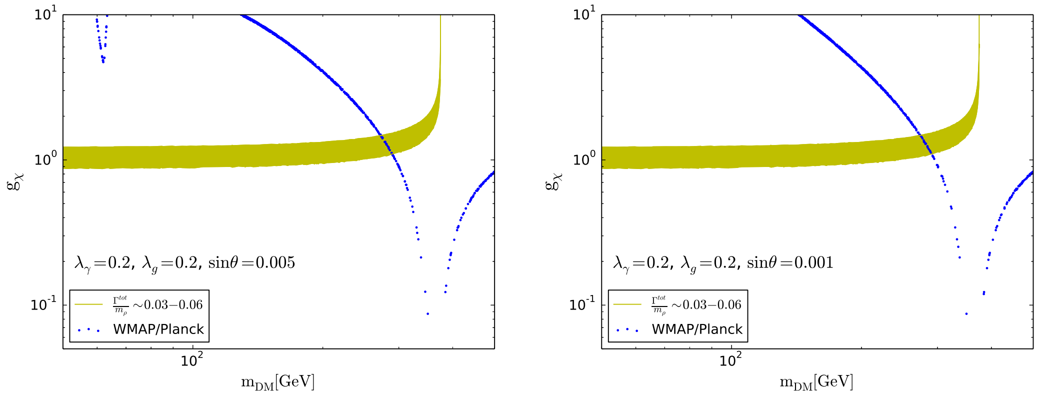

Figure 3: The same as Fig. 1 except that in the left panel $\sin\theta = 0.005$ and in the right panel $\sin\theta = 0.001$ are chosen.

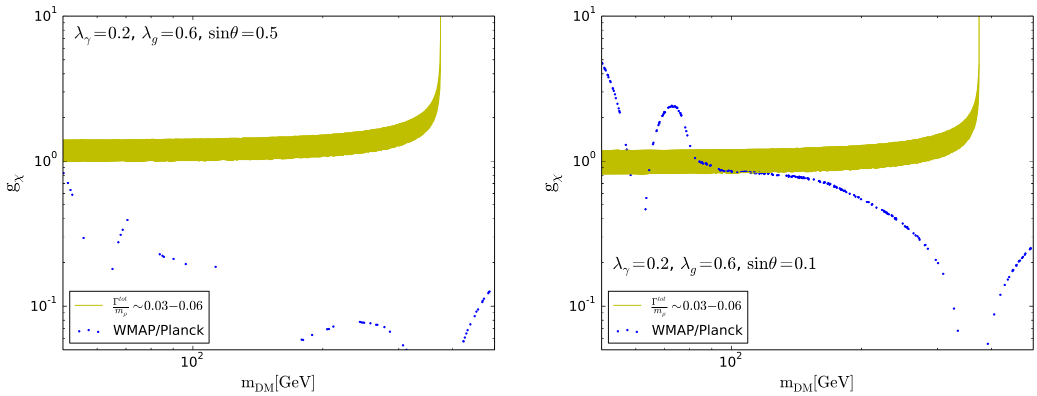

Figure 4: The viable parameter space in the dark sector is shown respecting the WMAP/Planck results. We display the region in the plane $m_{\rm DM} - g_\chi$ which satisfies the LHC constraint on the scalar total decay width, i.e., $\Gamma^{\rm tot}/m_\rho \sim 0.03 - 0.06$. The left panel corresponds to a mixing angle as $\sin\theta = 0.5$ and in the right panel $\sin\theta = 0.1$ is chosen. Here we set $\lambda_g = 0.6$ and $\lambda_\gamma = 0.2$.

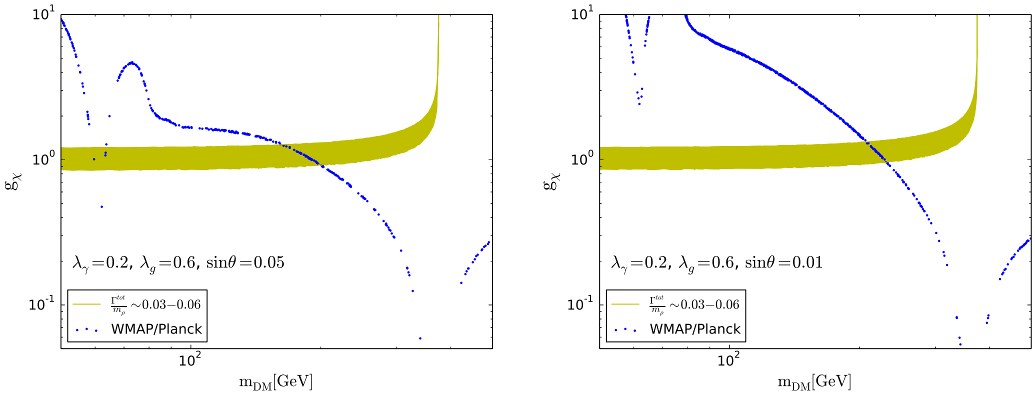

Figure 5: The same as Fig. 4 except that in the left panel $\sin\theta = 0.05$ and in the right panel $\sin\theta = 0.01$ are chosen.

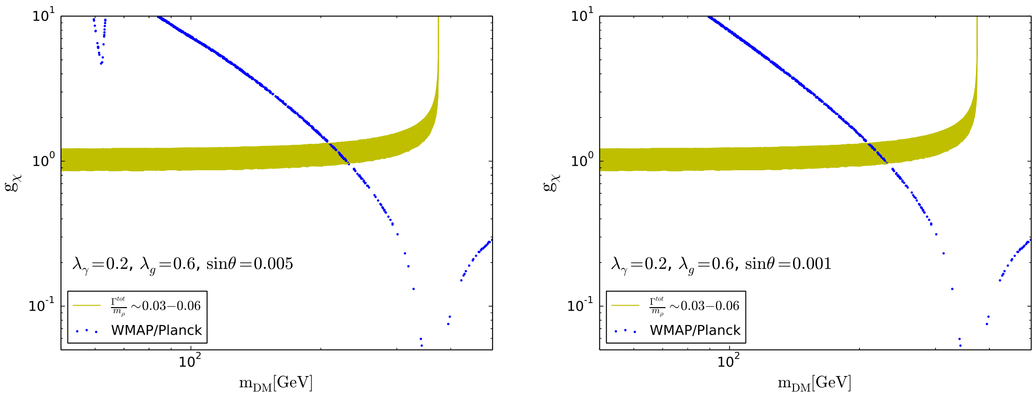

Figure 6: The same as Fig. 4 except that in the left panel $\sin\theta = 0.005$ and in the right panel $\sin\theta = 0.001$ are chosen.

with mass 750 GeV to be the observed resonance. Despite some believes in the literature, the model incorporating a pseudoscalar not only is ruled out, but in fact it is consistent with the decay width ~ 45 GeV reported by ATLAS for a wide range of dark matter masses. The dark matter candidate has been taken a Dirac fermion singlet with respect to SM gauge groups. The pseudoscalar interacts with the SM particles through the Higgs portal and through an gluon and photon effective operators. For the space of parameter bounded by the relic density $\Omega_{\rm DM} \sim 0.12$ measured by WMAP/Planck we have computed the various decay width and the total width. We have found that the parameter space bounded also by the decay width to be in the range $25-45$ GeV as measured by ATLAS would lead to dark matter masses within $88-280$ GeV. The diphoton signal cross section in the aforementioned DM mass range can be explained for the gluon effective coupling $\lambda_g \gtrsim 0.2$. The characteristic of this fermionic dark matter model is that the DM-nucleon cross section is velocity suppressed because the mediator has been taken a pseudoscalar.

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