Massive dark photons in a Higgs portal model

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Abstract.
An extension of the Standard Model with a hidden sector which consists of gauge singlets (a Dirac fermion χ and a scalar S) plus a vector boson V_μ (dark massive photon) is studied. The singlet scalar interacts with the Standard Model sector through the triple and quartic scalar interactions, while the singlet fermion and vector boson field interact with the Standard Model only via the singlet scalar. The scalar field generates the vector boson's mass. Perspectives for future e^-e^+ colliders is considered.

INTRODUCTION

The enigma of dark matter (DM) remains unsolved. Still one of the most evasive and fascinating mysteries in physics, the problem of the dark matter in the Universe stirs the imagination of most astronomers, cosmologists and particle physicists, that are convinced that at least 90% of the mass of the Universe is due to some non-luminous form of matter. Modernly, dark matter candidates converge to a variety of interesting and plausible candidates namely the *weakly-interacting massive particles* (WIMPs): Standard Model neutrinos [1], sterile neutrinos [2], axions [3], supersymmetric candidates [neutralinos, sneutrinos, gravitinos, axinos] [4]-[6] light scalar dark matter [7], dark matter from little Higgs models [8], Kaluza-Klein particles [9], superheavy dark matter [10]. An excellent review in theoretical and experimental aspects of dark matter can be found in [11]. In general they are present in theories of weak-scale physics beyond the Standard Model (SM) and give rise to appropriate relic abundance. Calculations have shown that stable WIMPs can remain from the earliest moments of the Universe in sufficient number to account for a significant fraction of relic dark matter density. This raises the hope of detecting relic WIMPs directly by observing their elastic scattering on targets. In the dark matter zoo many different types of particles have been introduced and their properties theoretically studied.

In the present work a renormalizable extension of the SM with a hidden sector which consists of SM gauge singlets (a singlet Dirac fermion χ and a singlet scalar S) plus a vector boson V_μ, which we shall call the *dark massive photon*, is studied. The singlet scalar interacts with the SM sector through the triple and quartic scalar interactions. The singlet fermion and vector boson field interact with the SM only via the singlet scalar. The scalar field generates the vector boson's mass.

THE MODEL

The model is defined by the following Lagrangian density

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_\chi + \mathcal{L}_S - g_\varphi S\,\bar{\chi}\chi + \mathcal{L}_I + \mathcal{L}_V \quad (1)$$

$$\mathcal{L}_\chi = \bar{\chi}(i\partial\!\!\!/ - m_{\chi_0})\chi \quad (2)$$

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S\,\partial^\mu S - V_S \quad (3)$$

$$\mathcal{L}_I = -\lambda_1 \Phi^\dagger\Phi S - \lambda_2 \Phi^\dagger\Phi S^2 \quad (4)$$

$$\mathcal{L}_V = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{4}\lambda_V S^2 V_\mu V^\mu - g_V \bar{\chi} V\!\!\!/ \chi \quad (5)$$

where $\mathcal{L}_{SM}$ is the Lagrangian density for the SM; Φ the SM Higgs and S a scalar field connecting with the dark sector; χ is the dark fermion singlet; the potential in $\mathcal{L}_S$ is defined as $V_S = \frac{m_0^2}{2} S^2 + \frac{\lambda_3}{3!} S^3 + \frac{\lambda_4}{4!} S^4$. The dark vector boson part is $\mathcal{L}_V$, with the field tensor given by $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$. The form of V_S clearly indicates the possibility of spontaneous broken symmetry in the model, which is parameterized by introducing $\langle S \rangle = x_0$. Considering spontaneous symmetry breaking in both sectors, the writing field SM Higgs as $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_0 + h(x) \end{pmatrix}$ and $S = x_0 + \varphi$, where $\mathcal{L}$ contains a quadratic form in h and φ, indicating that these are not mass eigenstates theory.

There remains the possibility that the interaction between the SM and the dark sector only through the scalar field: S with SM occurs exclusively through the Higgs boson, which includes the model in a class of theories known as *Higgs portal dark matter*. Writting $\mathcal{V} = V_S + V(\Phi^\dagger\Phi)$ and demanding that $\frac{\partial \mathcal{V}}{\partial h}\Big|_{v_0,x_0} = \frac{\partial \mathcal{V}}{\partial S}\Big|_{v_0,x_0} = 0$, one obtains

$$m_0^2 = -\frac{\lambda_3}{2} x_0 - \frac{\lambda_4}{6} x_0^2 - \lambda_2 v_0^2 - \frac{\lambda_1 v_0^2}{2x_0} \quad ; \quad \mu^2 = \lambda v_0^2 + x_0(\lambda_1 + \lambda_2 x_0)\,. \tag{6}$$

The neutral scalar states h and φ defined by $H_0 = (v_0 + h)/2$ and $S = x_0 + \varphi$ are mixed to yield the mass matrix given by [12]

$$\begin{aligned} M_{hh}^2 &= \frac{\partial^2 \mathcal{V}}{\partial h^2}\Big|_{h=\varphi=0} = 2\lambda v_0^2 \quad ; \quad M_{ss}^2 = \frac{\partial^2 \mathcal{V}}{\partial \varphi^2}\Big|_{h=\varphi=0} = \frac{\lambda_3 x_0}{2} + \frac{\lambda_4}{3} x_0^2 - \frac{\lambda_1 v_0^2}{2x_0} \\ M_{hs}^2 &= M_{sh}^2 = \frac{\partial^2 \mathcal{V}}{\partial \varphi \partial h}\Big|_{h=\varphi=0} = (\lambda_1 + 2\lambda_2 x_0) v_0\,. \end{aligned} \tag{7}$$

The two physical Higgs h_1 and h_2 are mixtures and the mass eigenstates are obtained by

$$\begin{aligned} h_1 &= \varphi \sin\theta + h \cos\theta \\ h_2 &= \varphi \cos\theta - h \sin\theta \end{aligned} \tag{8}$$

the mixing angle θ is defined by

$$\tan\theta = \frac{y}{1 + \sqrt{1 + y^2}} \quad ; \quad y = \frac{2M_{hs}^2}{M_{hh}^2 - M_{ss}^2}\,. \tag{9}$$

The h_1 and h_2 masses are

$$m_{1,2}^2 = \frac{M_{hh}^2 + M_{ss}^2}{2} \pm \frac{M_{hh}^2 - M_{ss}^2}{2} \sqrt{1 + y^2}\,. \tag{10}$$

In the present, the SM Higgs will be considered the h_1 field with mass $m_1 = 125$ GeV.

INTERACTION OF DARK PHOTONS

The connection of the SM with the dark sector is through the interaction with the scalar field S. In particular the term that describes the interaction between vector V_μ (dark photon) and S is $\frac{1}{4}\lambda_V S^2 V_\mu V^\mu$. After spontaneous symmetry breaking this term changes as

$$\frac{1}{4}\lambda_V S^2 V_\mu V^\mu \rightarrow \frac{\lambda_V x_0^2}{4} V_\mu V^\mu + \frac{\lambda_V x_0}{2} \varphi V_\mu V^\mu + \frac{\lambda_V}{4} \varphi^2 V_\mu V^\mu\,. \tag{11}$$

The first term on the RHS of (11) clearly reveals a mass term $m_V^2/2$ for the dark photon. This term shows that the coupling λ_V is related to the scale x_0 and to the vector boson's mass m_V by

$$\lambda_V = 2\,\frac{m_V^2}{x_0^2}\,. \tag{12}$$

By means of (12) one writes the two interaction Lagrangians of V_μ with φ as

$$\mathcal{L}_{\varphi V} = \sqrt{\frac{\lambda_V}{2}}\, m_V\, \varphi\, V_\mu V^\mu \quad ; \quad \mathcal{L}_{\varphi\varphi VV} = \frac{\lambda_V}{4}\, \varphi^2\, V_\mu V^\mu\, . \tag{13}$$

In this model, to describe the decay of the physical Higgs field h_1 into dark photons, one substitutes the $\sin\theta\, h_1$ contribution in φ of (8) into $\mathcal{L}_{\varphi V}$ obtaining a new expression:

$$\mathcal{L}_{hV} = \sqrt{\frac{\lambda_V}{2}}\, m_V\, \sin\theta\, h_1\, V_\mu V^\mu\, . \tag{14}$$

From (14) the Higgs partial decay width into a massive dark photon can be calculated resulting in

$$\Gamma(h_1 \to VV) = \frac{\lambda_V\, m_1^3\, \sin^2\theta}{64\,\pi\, m_V^2}\left(1 - 4\frac{m_V^2}{m_1^2} + 12\frac{m_V^4}{m_1^4}\right)\sqrt{1 - 4\frac{m_V^2}{m_1^2}}\, . \tag{15}$$

The parameter space can be generated from (15) for different mixing angles, assuming that this channel has a branching ratio $BR = \Gamma/\Gamma_{tot}$ of 10%. We shall consider $\Gamma_{tot} = 6.1$ MeV [13]. The result of this calculation is seen in Fig. (1).

The chances of observing dark photon pair production in the continuum might be higher in a cleaner environment like in e^-e^+ collisions. The $e^-e^+ \to VV$ annihilation cross-section is

$$\sigma = \frac{\lambda_V}{4\pi}\sqrt{1 - 4\,\frac{m_V^2}{s}}\left(\frac{m_e\, m_V\,(m_2^2 - m_1^2)\,\sin(2\,\theta)}{4\,v_0}\right)^2\left(2 + \frac{(s - 2m_V^2)^2}{4m_V^4}\right)\frac{1}{(s - m_1^2)^2\,(s - m_2^2)^2} \tag{16}$$

We have evaluated this cross-section at the energy range relevant for the ILC, $\sqrt{s} = 500$ GeV and at $\sqrt{s} = 3$ TeV relevant for the CERN CLIC [14]. The other parameters used are mixing angle 10^o and the coupling $\lambda_V \sim 1$. A comparison for different masses m_2 of the scalar field is considered. At this low value for the angle θ the mixing is small such that $h_1 \sim h$ and $h_2 \sim \varphi$. The results are shown in Fig. (3). Current efforts of studying Higgs physics at the LHC may result in difficulties to observe the dark matter effects. A solution could be to perform these studies of Higgs decays at e^-e^+ colliders. The fundamental drawback is that dark matter particles have extremely small pair production cross sections. As shown in the example of $e^-e^+ \to VV$, they are too small to be observed in colliders unless an enhancement for very high luminosities are made available.

ACKNOWLEDGMENTS

This research was supported by Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Universidade Federal do Rio Grande do Sul (UFRGS).

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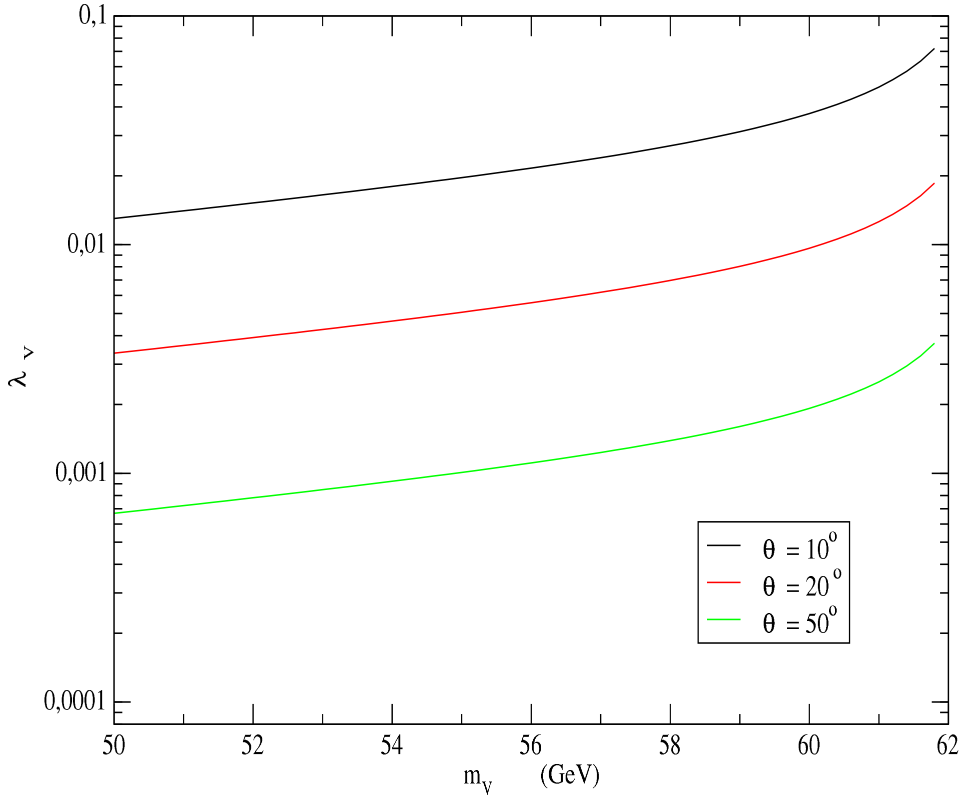

FIGURE 1. Parameter space relating the coupling λ_V to the dark photon mass m_V.

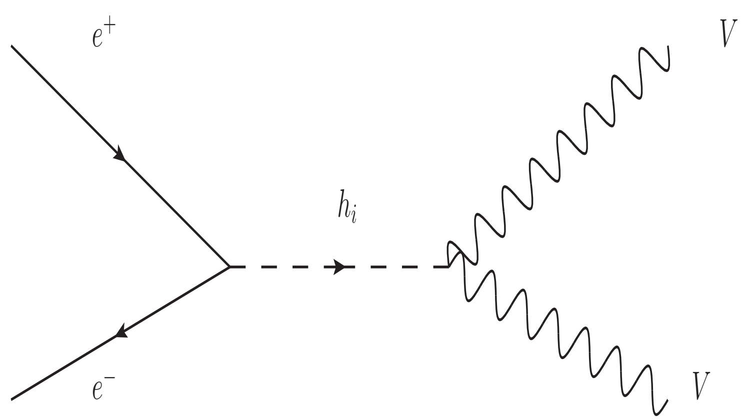

FIGURE 2. VV production from e^-e^+ annihilation.

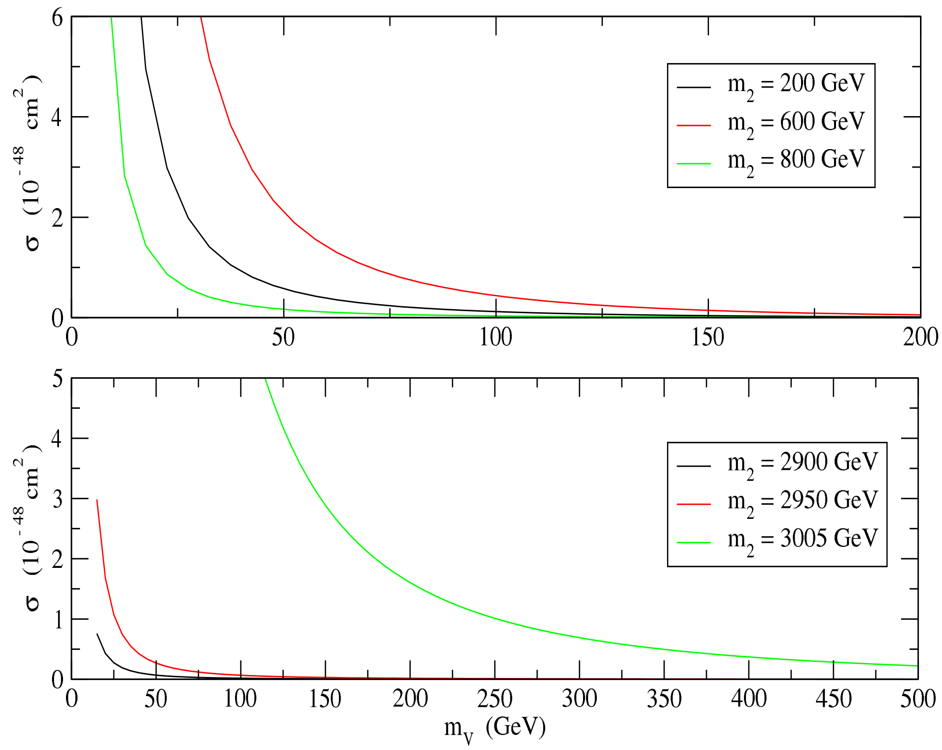

FIGURE 3. Mixing angle 10^o, $\lambda_V \sim 1$, $\sqrt{s} = 500$ GeV (upper) and $\sqrt{s} = 3$ TeV (lower).