PROCEEDINGS OF SCIENCE

# Form factor effects in a Higgs portal pionic dark matter model

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We investigate form factor effects in a higgs portal dark matter model with a new confining gauge theory in a hidden sector. If we consider the hidden gauge theory with light fermions coupling to the standard model sector via higgs portal, the lightest hadron-like state, e.g. meson-like state or baryon-like state, can be stable due to an accidental symmetry in the hidden sector, and thus dark matter (DM) candidate. In this presentation, we focus on pion-like state DM that is the pseudo Nambu-Goldstone boson resulting from chiral symmetry breaking in the hidden sector, and show that the higgs portal interaction is related to scalar form factor of DM and the enhancement effects by the form factor tend to relax constraint on DM mass.

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## 1. Introduction

It is of a definitely evidence that much of matter density in the observable universe consists of the invisible components [1, 2], dark matter (DM), whose properties have yet been unknown so much, though. If the DM abundance could be explained as thermal relic produced in plasma of relativistic particles in early universe, the strength of the interaction between DM and the standard model (SM) could naïvely be determined. We therefore expect, for just the right magnitude of coupling to explain the invisible matter density, that the direct signals of DM can be measured in many typical models near future. In contrast to the anticipation, however, the DM direct search experiments in the ground by using big target and the Large Hadron Collider (LHC) experiments in CERN can measure no definite sign so far.

Accordingly, it may be possible that the reason of the null signal of DM is because the magnitude of the DM coupling with the SM particles at freeze-out differs from ones at energy scale of the direct detection experiments or the collider experiments. In this presentation, we investigate this possibility by using a model in which that the pseudo Nambu-Goldstone bosons (pNGBs) from spontaneous chiral symmetry breaking in the hidden strong dynamics can be DM candidates. It is also assumed that the hidden sector couples with the SM sector only through the Higgs portal. Since the interactions of the pNGBs take the form of the derivative interactions due to the property of them parametrizing the broken symmetry space, there is an enhancement effects of the coupling strength at freeze-out era when DM density are determined, and simultaneously a suppression of that of the direct detection experiments.

This presentation is constructed as follows. In Section 2, we present a simplified model with a confining gauge theory in the hidden sector that is motivated to realize the idea, and the DM candidate we will focus on. Section 3 is an illustration of the form factor effects. The strategy of our analysis is also presented in this section. We show the results in Section 4, and summarize in Section 5.



## 2. Model

We consider an extension of the SM with a vector-like $SU(3)$ confining gauge theory in the hidden sector

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_{i=1,2} \left( \bar{Q}_i \left( i\gamma^\mu D_\mu - m_Q \right) Q_i - \frac{1}{\Lambda}(H^\dagger H)\bar{Q}_i Q_i \right), \tag{2.1}$$

with $H$ the SM doublet higgs field and $Q_i$ two flavor hidden quarks in the fundamental representation which couple with the SM sector only via Higgs portal. $\mathscr{L}_{SM}$ includes all the ordinary SM interactions. Here we assume that both the hidden current quark mass $m_Q$ and the higgs portal coupling $1/\Lambda$ are flavor universal. It is also assumed that two hidden quarks are somewhat lighter than the hidden confining scale $\Lambda_h$. The gauge sector is therefore very similar to the ordinary QCD with $u$ and $d$ quarks except the hidden quarks carry no electromagnetic charges. Since the model has a higher dimensional operator in the last term of Eq.(2.1), some extensions [3, 4, 5, 6, 7, 8, 9, 10] are needed if one want a renormalizable model. As we will see below, however, what follows can be applied for the renormalizable extension models.

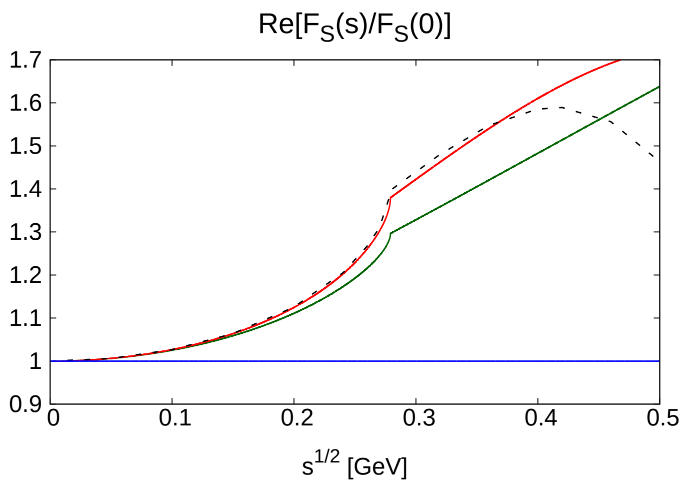


**Figure 1:** The real part of the scalar form factor of pion in the SM QCD [13]. Blue, green, red and dash line show $p^2, p^4, p^6$ order estimate of the chiral perturbation theory and the experimental behavior, respectively.

There is an approximate chiral symmetry $\mathscr{G} = SU(2)_L \times SU(2)_R$ under which the hidden quarks transform

$$Q_i \to (e^{i\gamma_5 \theta^a \tau^a/2} Q)_i, \tag{2.2}$$

that is broken explicitly by the hidden current quark mass and the higgs portal coupling. Given that the symmetry in the hidden sector is spontaneously broken down to the diagonal subgroup $\mathscr{H} = SU(2)_V$ due to hidden quark-antiquark pair condensation in vacuum $\langle \bar{Q}Q \rangle \neq 0$, then the pseudo Nambu-Goldstone bosons (hidden pions $\Pi^a$) appear, parametrizing the coset space $\mathscr{G}/\mathscr{H}$. Thanks to the explicit breaking terms and $SU(2)_V$ flavor symmetry, these bosons are massive and stable and can therefore be good DM candidates. It should be noted that we can neglect the contribution of the lightest hidden baryon, whose stability is guaranteed by hidden baryon number conservation, to the invisible matter density in our universe[1] because in TeV scale hidden confining theory that we are now interested in the symmetric relic density is expected to become much less than the observed DM abundance. We will therefore focus on the hidden pion dark matter below.

## 3. Form factor effect

Since the hidden sector communicates with the SM sector only through the higgs exchange, we need to know the higgs portal interaction of the hidden pions in more detail to develop DM phenomenology. Now there are only light hidden quarks in the hidden sector, the portal interaction is proportional to the scalar form factor $F_S(q^2)$,

$$\lambda_{h\Pi\Pi}(q^2) = \frac{v}{\Lambda} F_S(q^2), \tag{3.1}$$

[1]See e.g. Refs. [11, 12, 9] and the references therein.

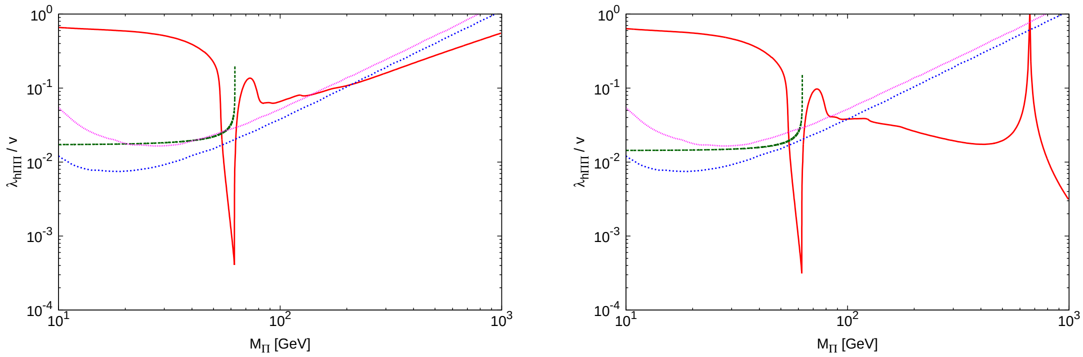


**Figure 2:** The experimental bounds in the plane of the hidden pion mass $M_\Pi$ and the portal coupling $\lambda_{h\Pi\Pi}$. Left panel shows the $p^2$ order approximation and right panel the $p^6$ order approximation with $F_\Pi = 50$ GeV in chiral perturbation theory, respectively. Red line can explain the present DM relic density [16], and blue, magenta and green lines are bounds from LUX [17], XENON100 [18] experiments and higgs invisible branching ratio at the LHC experiments [19, 20], respectively.

where $\langle \Pi^a(p_1)|\bar{Q}Q(q)|\Pi^b(p_2)\rangle \equiv F_S(q^2)\delta^{ab}$ with momentum $q = p_1 - p_2$ the higgs carries. Then, the evaluation of the form factor in the hidden strong dynamics leads directly to the knowledge of the interaction between the hidden pion DM and the SM sector.

We expect that the form factor behaves similarly to that of the SM QCD because the gauge and flavor structures of both theories are also similar. In Fig.1, for an illustration, we therefore show the real part of the form factor in the SM QCD with respect to transferring energy. Dash line in the figure shows the experimental behavior of the form factor of the pion. Blue, green and red lines also show the prediction of the chiral perturbation theory up to $p^2, p^4$ and $p^6$ order, respectively. From the figure, we find that there is an enhancement of the form factor, i.e. an enhancement of the portal interaction, as the energy the higgs carries increases. Note that the $p^2$ order chiral perturbation estimate corresponds to the constant interaction that is used in the previous works [4, 5, 6], and the $p^6$ order approximation are needed if we want to take account into the enhancement effect at freeze-out, $q^2 \sim 4M_\pi^2$, correctly. In our numerical analysis, the chiral perturbation theory up to $p^6$ order is used to estimate the scalar form factor.

## 4. Results

We show in Fig.2 all the limitations from the experimental observations in the plane of DM mass $M_\Pi$ and the portal coupling $\lambda_{h\Pi\Pi}$. As the experimental limits, the present DM abundance [16] (red line), the null signal of DM-nucleon scattering in the direct detection experiments [17, 18] (blue and magenta lines) and the higgs invisible decay [19, 20] (green line) are taken account into. The relic abundance of the hidden pion is evaluated by using the micrOMEGAs 3.6.9.2. Left panel shows the case that we estimate the form factor in the $p^2$ order chiral perturbation theory and right panels up to the $p^6$ order approximation with $F_\Pi = 50$ GeV respectively. From the figure, we find that while lower limit on DM mass is $\sim 200$ GeV at $p^2$ order, the limit is relaxed down to $\sim$100 GeV up to at $p^6$ order with $F_\Pi = 50$ GeV.

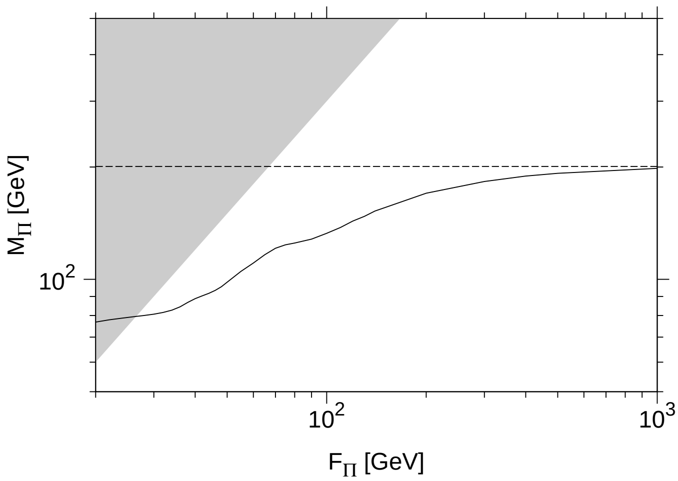


**Figure 3:** Exclusion region of the model in the $(F_\Pi, M_\Pi)$ plane. Dash and solid line show the limit in $p^2$ and $p^6$ order chiral perturbative analysis respectively. The region below the lines are excluded by the experimental observations, the DM relic density, DM direct detection experiments and the higgs invisible branching ratio. Gray region is where the higher order contributions of the chiral perturbative expansion dominate and our analysis is therefore invalid.

We can see a singular behavior of red line in the right panel of Fig.2. The appearance is caused by the fact that the $p^2$ order and $p^4$ order contributions to the scalar form factor are cancelled out there, and therefore means that the perturbative description is broken down. In fact, this singular behavior appears at $M_\Pi \sim 4\pi F_\Pi \sim \Lambda_h$ where the validity of the chiral perturbation theory cannot be retained.

In Fig.3, we show the exclusion regions in the $(F_\Pi, M_\Pi)$ plane. Dash and solid lines express the limits at $p^2$ and $p^6$ order respectively. The region below each line is excluded by the experimental constraints. Where the reliability of the perturbative expansion is broken down is colored gray. From the figure, we find that lower limit set on DM mass is relaxed from $\sim$200 GeV to $\sim$80 GeV at most as the order of approximation in chiral perturbation theory that we use in estimation of the scalar form factor is changed from $p^2$ to $p^6$. We therefore conclude that if we consider the pion-like particle DM candidate arising from the TeV scale confining gauge theory in the hidden sector, the enhancement effects of the portal interaction by the form factor should be included appropriately.

## 5. Summary and Discussion

We investigate in this presentation the form factor effects in a Higgs portal DM model where the pseudo Nambu-Goldstone bosons (hidden pions), resulting from chiral symmetry breaking in the confining hidden sector, are the predominant component of DM. If the hidden sector has only light hidden quarks, the higgs portal interaction of the hidden pions is proportional to the scalar form factor and can be enhanced (or suppressed) at high energy. Analyzing this form factor by using the chiral perturbative approach up to $p^6$ order, we find that there is an enhancement of the portal interaction at freeze-out at most by tens of percents compared to one at energy scale of the direct detection experiments, which leads to relaxation of the constraint on this type of DM.

Recently, in a hidden pion DM model, although in a strongly interacting massive particle (SIMP) dark matter context, the possibility that the higher order contributions in chiral perturbation theory significantly change the lowest order prediction and may lead to the disfavored consequence have been discussed [14]. Our analysis may therefore give a significant correction for analysis of many similar models. The cases that there is flavor symmetry violation of the light hidden quarks or the hidden sector contains heavy hidden quarks are now in progress.

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