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[157] Possible effects of the composite dark matter at the linear collider

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Abstract

We consider the model of the composite dark matter based on the QCD-like SU(N) hidden color confining gauge theory.
Our meson-like dark matters (call it dark mesons) are a bounded state of dark quark (ψ) and anti-dark quark ($\overline{\psi}$) pairs. This dark matter sector connects to the Standard model via a real singlet scalar particle. The SU(N) hidden color gauge sector in the dynamical chiral symmetry breaking generates Nambu-Goldstone bosons ($\tilde{\pi}$ dark meson) and massive composite scalar bosons ($\tilde{\sigma}$ dark meson) simultaneously. A real singlet scalar particle gives the current mass for the dark quark. The current mass for dark quark breaks explicitly chiral symmetry. Nambu-Goldstone bosons are massive, meaning they are dark matter candidates. In the dark mesons of SU(N) hidden color, the chiral partner of the $\tilde{\pi}$ meson is the $\tilde{\sigma}$ meson (iso scalar-scalar). $\tilde{\sigma}$ is also a candidate as dark matter. We will investigate the invisible process for the Higgs boson's decay at the future linear collider.

The Model

The hidden sector Lagrangian:

$$\mathcal{L}_H = -\frac{1}{2}\mathrm{Tr}F^2 + \mathrm{Tr}\overline{\psi_i}\left(i\gamma^\mu\partial_\mu + g_H\gamma^\mu G_\mu + g'Q\gamma^\mu B_\mu - y_i\phi\right)\psi_i$$

$$B_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu,\ g' = e/\cos\theta_W,\ i = 1,2,3$$

If the diagonal component of the Yukawa coupling,

$$y_1 = y_2 \neq y_3.$$

➡Flavour symmetry breaking: $SU(3) \to SU(2)_V \times U(1)_{\tilde{B}}$

In our present analysis, we omitted ψ_3. We assume that the mesons of which ψ_3 is a constituent are heavy mass.

The Lagrangian of the Higgs portal is as follows.

$$\mathcal{L}_{portal} = -\frac{1}{2}\mu_H^2(H^+H) - \frac{1}{2}\mu_s^2\phi^2 - \lambda_H(H^+H)^2 - \frac{1}{4}\lambda_s\phi^4 - \frac{1}{2}\lambda\phi^2(H^+H)$$

Dark quarks are connected to the SM through the Yukawa couplings of Higgs and a singlet scalar particle ϕ.

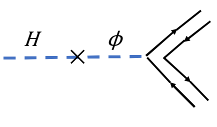
💡 **Dark hadrons can be observed by the collider experiments.**

We have assumed that the dark matter section is simply a scaled-up version of QCD.
A part of the effective Lagrangian depending on ϕ:

$$\mathcal{L}_{int} = g_\pi\phi\left(\widetilde{\pi^+}\widetilde{\pi^-} + \widetilde{\pi^-}\widetilde{\pi^+} + \widetilde{\pi^0}\widetilde{\pi^0}\right) + g_\sigma\phi\tilde{\sigma}\tilde{\sigma}$$

In the dark mesons of SU(N) hidden color, the chiral partner of the $\tilde{\pi}$ meson is the $\tilde{\sigma}$ meson (iso scalar-scalar). $\tilde{\sigma}$ is also a candidate as dark matter.

Decay modes & decay width:



$\bar{\psi}\psi \to \widetilde{\pi^+}, \widetilde{\pi^-}, \widetilde{\pi^0}, \tilde{\sigma}$

$\overline{(\bar{\psi}\psi)} \to \widetilde{\pi^-}, \widetilde{\pi^+}, \widetilde{\pi^0}, \tilde{\sigma}$

Assume: $g_\pi = g_\sigma \equiv g$

$$\Gamma_{\phi\to Dark\ mesons} \propto \frac{g^2}{4\pi}\frac{1}{M_\phi^2}\sqrt{\left(\frac{M_\phi}{2}\right)^2 - (\tilde{m}_{Dark\ mesons})^2}$$

Total decay width of ϕ:

$$\Gamma_{\text{total}}^{\phi} = \Gamma_{\phi\to\widetilde{\pi^+}\widetilde{\pi^-}} + \Gamma_{\phi\to\widetilde{\pi^0}\widetilde{\pi^0}} + \Gamma_{\phi\to\tilde{\sigma}\tilde{\sigma}}$$

Method (The case of $SU(3)$ hidden color gauge sector)

We use an effective theory for dark matter interactions in the framework of the linear sigma model. We scale up the dark meson mass ,$m_{\widetilde{DM}}$, by giving the hadron vacuum expectation value v, and the dark matter energy scale v_{DM}.

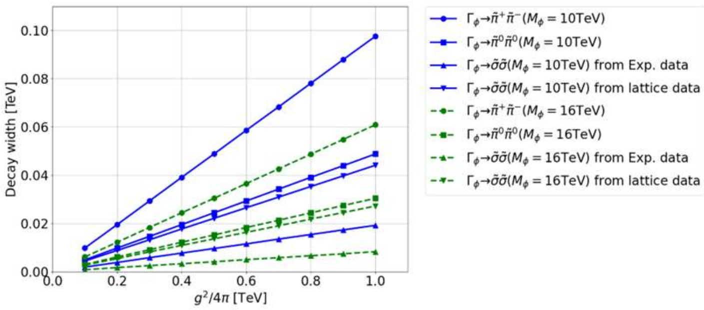
$$m_{\widetilde{DM}} = m\frac{v_{DM}}{v}$$

In hadron physics, the experimental value of σ is not fixed, so the results of the LATTICE calculations are used as a reference. This result does not fully incorporate the effect of chiral symmetry since the simulation is based on the Wilson action. For the other mesons, the median experimental value was used [1]. A recent analysis shows that the dark pion has a mass of 1.8 TeV [2].

[1] S. Navas et al. (Particle Data Group), to be published in Phys. Rev. D 110, 030001 (2024)
[2] T. Abe, R. Sato, T. Yamanaka, arXiv:2404.03963v1 [hep-ph] (2024)

Result

Decay width



Brunching ratio

v_{DM}[TeV]	M_ϕ[TeV]	$\tilde{m}_\pi$[TeV]	$\tilde{m}_\sigma$[TeV]	$\frac{\Gamma_{\phi\to\widetilde{\pi^+}\widetilde{\pi^-}}}{\Gamma_{\text{total}}}$	$\frac{\Gamma_{\phi\to\widetilde{\pi^0}\widetilde{\pi^0}}}{\Gamma_{\text{total}}}$	$\frac{\Gamma_{\phi\to\tilde{\sigma}\tilde{\sigma}}}{\Gamma_{\text{total}}}$
1	10	1.08	4.615	0.5893	0.2946	0.1161
1	10	1.08	2.35	0.5123	0.2561	0.2316
1.67	16	1.8	7.715	0.6113	0.3057	0.0830
1.67	16	1.8	3.94	0.5137	0.2569	0.2294

Summary

The decay mode $\phi \longrightarrow \widetilde{\pi^0}\,\widetilde{\pi^0}$ is a visible process because it is $\widetilde{\pi^0} \longrightarrow$2γ. The other decay modes are invisible processes. We assume that $\tilde{\sigma}$ decay into $\widetilde{\pi^+}\,\widetilde{\pi^-}$ and $\widetilde{\pi^0}\,\widetilde{\pi^0}$, do not decay into 2γ (In hadron physics, it is not yet known whether σ meson decay into photons or not). $\widetilde{\pi^+}$, and $\widetilde{\pi^-}$ could be stable dark matter. We are supposed to identify dark matter through an invisible process at the future linear collider.

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