Snowmass2021 - Letter of Interest

Dark Pion Searches at Colliders and High Intensities

☐ (EF01) EW Physics: Higgs Boson properties and couplings
☐ (EF02) EW Physics: Higgs Boson as a portal to new physics
☐ (EF03) EW Physics: Heavy flavor and top quark physics
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■ (EF09) BSM: More general explorations
☐ (EF10) BSM: Dark Matter at colliders
■ (RF06) Dark Sector Studies at High Intensities

Contact Information:

Hsin-Chia Cheng (Center for Quantum Mathematics and Physics (QMAP), Department of Physics, University of California, Davis, CA, USA) [cheng@physics.ucdavis.edu]
Lingfeng Li (Jockey Club Institute for Advanced Study, The Hong Kong University of Science and Technology, Hong Kong S.A.R.) [iaslfli@ust.hk]
Ennio Salvioni (CERN, Geneva, Switzerland) [ennio.salvioni@cern.ch]
Christopher B. Verhaaren (Department of Physics, University of California, Irvine, CA, USA)[cverhaar@uci.edu]

Abstract:

We plan to study the phenomenology and experimental searches of the dark pions, which are the lightest hadrons in a hidden sector confining gauge theory. Such a scenario arises in many extensions of the Standard Model (SM). We consider that the leading interactions between the light hidden sector quarks and the SM particles come from the mixing of the light hidden quarks with heavy electroweak doublet states through Higgs Yukawa couplings, so that the leading portals are the Z and Higgs bosons. The plan is to study their productions and decays, and the search reaches at current and future experimental facilities, including high energy colliders and low energy, high intensity fixed target experiments.

1 Introduction

Hidden sectors occur in many extensions of the Standard Model (SM), for example, in the neutral naturalness solutions of the hierarchy problem. They also provide a natural setting for the Universe's dark matter (DM). If hidden sector states interact very weakly with the SM sector then existing experimental searches cannot detect them, and they can be quite light. A widely motivated and interesting possibility is that the hidden sector contains a confining gauge force which forms dark hadrons. Experimental searches for these dark hadrons require detailed investigations of their interactions and experimental signatures. If the hidden confining gauge group contains more than one flavor of light fermions, the lightest dark hadrons are expected to the pseudo-Nambu-Goldstone bosons – dark pions. The other dark hadrons, unless stabilized by symmetries, are expected to decay quickly to the dark pions once they are produced. In this Letter of Interest (LOI) we describe the dark pion model and outline our plan to study the associated phenomenology, as well as the future reach of experimental searches in the sub-GeV to tens of GeV mass range.

Hidden sector states may interact with SM particles through various "portals." Light hidden sector fermions can develop interactions with SM particles by mixing with heavy electroweak doublets through Higgs couplings. This occurs naturally in some neutral naturalness models where the heavy fermions are responsible for regularizing the Higgs potential.[?] In this case the main portals between the light hidden states and SM particles are the Z boson and the Higgs boson. Which one is more important for the production depends on the model. If both left-handed and right-handed light hidden quarks mix with heavy states with comparable strengths, the production of the hidden sector states at colliders is dominated by the Higgs. On the other hand, if the mixing between the light and heavy fermions is only in one handedness, production mainly goes through the Z.[?] After they are produced, unstable dark hadrons quickly decay down to dark pions. The decays of the dark pions are governed by their interactions with the Z. The lifetimes and decay patterns of the dark pions depend on many factors, including the dark pion masses, the strength of the interactions, and the explicit breaking of the global (isospin) symmetry of the dark pion sector. As a result, many experimental possibilities can be realized in this model. Our plan is to perform a comprehensive study of different experimental searches.

2 The Low Energy Effective Theory for the Dark Pions

Consider a hidden confining gauge group $SU(N_c)$ with $N > 1$ flavors of light fermions ψ_L^i, ψ_R^i, $i = 1, \cdots, N$ in the fundamental representation of the gauge group. These complete SM singlets have masses below the strong scale of the $SU(N_c)$ gauge group Λ, which connections to Higgs naturalness motivate to be no larger than tens of GeV. In addition, we assume that there are heavy electroweak doublet fermions Q_L^i, Q_R^i (with hypercharge $-1/2$) which also transform in the fundamental representation of $SU(N_c)$. They can couple to the light fermions via the Higgs field, with the Lagrangian

$$\mathcal{L} = -H\overline{Q}_L \boldsymbol{Y}\psi_R - H\overline{Q}_R \widetilde{\boldsymbol{Y}}\psi_L - \overline{\psi}_L \boldsymbol{\omega}\psi_R - \overline{Q}_L \boldsymbol{M} Q_R + \text{H.c.}\,, \tag{1}$$

where $\boldsymbol{Y}$, $\widetilde{\boldsymbol{Y}}$, $\boldsymbol{\omega}$, and $\boldsymbol{M}$ are all $N \times N$ matrices in the flavor space. Without loss of generality, we can use flavor rotations into a basis where the mass matrices $\boldsymbol{\omega}$ and $\boldsymbol{M}$ are diagonal with positive entries. The masses M_i of the heavy $Q_{L,R}$ are assumed to be at least $\sim$ TeV, so at low energies we can integrate $Q_{L,R}$ out and insert the Higgs vacuum expectation value to obtain a low energy effective Lagrangian.

The leading interaction of the Higgs boson to the light hidden fermions comes from a dimension-5 operator

$$\frac{v}{2}\overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-1} \boldsymbol{Y}\psi_R h + \text{H.c.}\,, \tag{2}$$

where $v \approx 246$ GeV. The current bounds on Higgs decays already put significant constraints on $\widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-1} \boldsymbol{Y}$. However, if $\widetilde{\boldsymbol{Y}} = 0$ (or $\boldsymbol{Y} = 0$) due to some chiral symmetry, this interaction vanishes and the leading effects come from dimension-6 operators. In that case, the leading interaction of the Higgs boson to the hidden sector is through the dark gluons,

$$c_Q v \mathrm{Tr}\left(\boldsymbol{Y}^\dagger \boldsymbol{M}^{-2} \boldsymbol{Y} + \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-2} \widetilde{\boldsymbol{Y}}\right) \frac{\alpha_d}{48\pi} h \hat{G}^a_{\mu\nu} \hat{G}^{a\mu\nu} \,, \tag{3}$$

where $c_Q \sim O(1)$ arises from integrating out a $Q_{L,R}$ loop, and α_d is the hidden gauge coupling. The effective interaction between the Z boson and light hidden fermions is also from dimension-6 operators, and is given by

$$\frac{g_Z v^2}{4} \overline{\psi}_R \boldsymbol{Y}^\dagger \boldsymbol{M}^{-2} \boldsymbol{Y} \gamma^\mu \psi_R Z_\mu + \frac{g_Z v^2}{4} \overline{\psi}_L \widetilde{\boldsymbol{Y}}^\dagger \boldsymbol{M}^{-2} \widetilde{\boldsymbol{Y}} \gamma^\mu \psi_L Z_\mu \,, \tag{4}$$

where $g_Z = \sqrt{g^2 + g'^2}$. This leads to the Z branching ratio

$$\mathrm{BR}(Z \to \overline{\psi}\psi) \approx 1.1 \times 10^{-5} \left\{ \mathrm{Tr}\left[\left(\boldsymbol{Y}^\dagger \boldsymbol{Y}\right)\right]^2 + (\boldsymbol{Y} \to \widetilde{\boldsymbol{Y}}) \right\} \left(\frac{2\,\mathrm{TeV}}{M}\right)^4 \,, \tag{5}$$

for $\boldsymbol{M} = M \times \mathbf{1}$. In general, at high energy colliders Z is much more copiously produced than h, hence for $\widetilde{\boldsymbol{Y}} = 0$ the leading production of hidden sector particles is through these Z decays.

After production, the hidden sector particles form dark hadrons and all unstable states produce dark pions. The dark pions can decay back to SM particles through the Z interaction in (**??**) if the global symmetry under which they transform is explicitly broken. They are typically long-lived on collider time scales, with their lifetime depending on the size of the explicit symmetry breaking. The branching ratios to SM leptons, hadrons, and photons depend on the dark pion mass, which affects how the search strategies are optimized.

3 Proposals

In this LOI we propose the study of several dark pion topics:

- Production of dark pions:
  - Production via Higgs and Z portal at high energy colliders.
  - Production via Z portal in low energy, high intensity experiments.
- Decays of dark pions (decay length, branching ratios, etc.).
- Dark pion searches at high energy colliders:
  - Searches at the (HL-)LHC, including CMS, ATLAS, and LHCb.
  - Searches at future Z-factories and Higgs factories.
- Dark pion searches at high intensity fixed target experiments.

References

[1] H.-C. Cheng, L. Li, E. Salvioni, and C. B. Verhaaren, "Singlet Scalar Top Partners from Accidental Supersymmetry," *JHEP*, vol. 05, p. 057, 2018.

[2] H.-C. Cheng, L. Li, E. Salvioni, and C. B. Verhaaren, "Light Hidden Mesons through the Z Portal," *JHEP*, vol. 11, p. 031, 2019.