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$Sp(4)$ SIMP Dark Matter on the Lattice

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The Strongly Interacting Massive Particle (SIMP) paradigm has recently been increasingly studied. It provides Dark Matter (DM) candidates as pseudo-Goldstone bound-states of dark fermions under a new gauge group. In this scenario freeze-out occurs through $3 \to 2$ dark matter self-annihilation and points to DM particles with masses of $O(100\text{ MeV})$. We study the spectrum of the lightest mesons of $Sp(4)$ gauge theory with two massive non-degenerate fundamental Dirac fermions using lattice gauge theory. The theory has a total of five pseudo-Goldstone bosons which can self-annihilate. In particular, we investigate the breaking of the flavor symmetry when making the fermions non-degenerate. We report that one pseudo-Goldstone is lighter than the others while the remaining heavier four pseudo-Goldstones are still mass-degenerate.

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1. Introduction

The nature of dark matter is one the most challenging problems in current particle physics. Recently a class of strongly-interacting, confining gauge theories with a number of massive fermions has gained some interest as dark matter candidates [1–4]. In these theories dark matter is made up of the pseudo-Goldstones bosons associated with the breaking of the approximate chiral symmetry and dark matter can self-annihilate through $3 \to 2$ processes in the early universe. In addition non-degenerate fermions are interesting because they can establish a mass hierarchy in the dark sector. As an example of such a sector we study here $Sp(4)$ gauge theory with 2 fundamental non-degenerate Dirac fermions in isolation. To the best of our knowledge this is the first time that strong isospin breaking has been studied in a non-$SU(N)$ gauge theory on the lattice. Here we present first, exploratory results for the masses and decay constant of the pseudo-Goldstones and the multiplet containing the vector nonsinglet mesons.

2. Global Symmetries and Observables

The fundamental representation in any symplectic group, such as $Sp(4)$, is pseudo-real. This entails relations between particles and anti-particles and their Weyl components. Therefore, this theory has a global $U(4)_I$ isospin symmetry in case of vanishing masses. It is broken by the axial anomaly down to $SU(4)_I$. Spontaneous chiral symmetry breaking and/or degenerate fermions break this symmetry further to $Sp(4)_I$. In case of non-degenerate masses the symmetry is broken down further to $SU(2)_u \times SU(2)_d$ [5, 6]. These relate the Weyl components of the two dark fermion flavors, the (dark) up and the (dark) down.

As this theory confines the physical degrees of freedom are hadrons. Due to the relation between particles and anti-particles and the even number of colors all hadrons are bosons, and made from an even number of fermions. In addition to the usual quark-antiquark mesons additional diquark (quark-quark and antiquark-antiquark) bound-states appear. It can be shown that these states have the same mass as their mesonic counterparts but have flipped parity [7, 8]. We will therefore restrict ourselves to the study of quark-antiquark Goldstones and vector bound-states. Note, that the corresponding quark-quark states are, however, scalars and axialvectors.

Most interesting for dark matter physics are the properties of the lightest states. These are the pseudo-Goldstone bosons as well as (likely) the nonsinglet vector mesons. In the mass degenerate case these quantities have already been studied in [9, 10]. Because the global symmetry is further broken by the non-degenerate quark masses, these hadrons will no longer be degenerate: Similar to QCD, the flavored and unflavored mesons will obtain different masses and decay constants. In the present case the 5 Goldstones decompose into 2 fundamental representations of each of the SU(2) groups and one singlet. Likewise the 10-plet of flavored spin-one mesons [11] decomposes into a 6-plet of flavored particles and a 4-plet of unflavored particles [6]. We will denote the unflavored pseudoscalar by π^0 and the flavored ones as $\pi^\pm$ in analogy to QCD. The other pair is made up of quarks, and remains degenerate to the $\pi^\pm$ [6]. Similarly we consider the flavored vector spin-one $\rho^\pm$ and the unflavored vector spin-one ρ^0.

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3. Lattice Setup

We use a variant of the HiRep code [12] adapted for $Sp(N)$ gauge theories [9] to simulate $Sp(4)$ gauge theory using the standard Wilson gauge action. We include two fundamental Dirac-Wilson-fermions with non-degenerate masses using the RHMC algorithm. We fix the lighter of the two quark masses by requiring an approximate ratio of $m_\rho/m_\pi \approx 1.25$ in the degenerate case. This is suggested by dark matter phenomenology [13], which prefers stable vector particles and Goldstones of order or above the confinement scale. The other bare quark mass is then incrementally increased. We considered a lattices of the size $L^3 \times T = 14^3 \times 24$ for which the finite volume effects are under control. Denoting the (dark) quark fields as u and d these hadrons are described by operators O_Γ^f, specifically

$$O_\Gamma^\pm(x,y) = \bar{u}(x)\Gamma d(y) \tag{1}$$

$$O_\Gamma^0(x,y) = \bar{u}(x)\Gamma u(y) - \bar{d}(x)\Gamma d(y). \tag{2}$$

The masses are extracted from the exponential fall-off of the zero-momentum correlator on a lattice of temporal extent T and spatial extent L at large times t

$$C_O(\vec{p}, t_x - t_y) = \frac{1}{L^3}\sum_{\vec{x},\vec{y}} e^{-i\vec{p}(\vec{x}-\vec{y})}\langle O(\vec{x},t_x)O^\dagger(\vec{y},t_y)\rangle \tag{3}$$

$$C_{O_\Gamma}(0,t) \xrightarrow{t\to\infty} \frac{|\langle 0|O_\Gamma|GS\rangle|^2}{2m_{\text{meson}}L^3}\left(e^{-m_{\text{meson}}t} + e^{-m_{\text{meson}}(T-t)}\right) \tag{4}$$

where $|GS\rangle$ is the ground state of the meson sourced by the interpolator O_Γ.

4. Results

The results for the flavored and unflavored pseudo-Goldstone and vector meson masses are depicted in figures 1 as a function of the mass difference of the pseudo-Goldstones. The results are given in units of the pseudo-Goldstone mass at degeneracy.

We see a clear separation of the flavored and unflavored meson states and can conclude that they are no longer mass-degenerate. For both the pseudo-Goldstones and the vectors the unflavored ones are lighter than the others. Furthermore, at sufficiently large fermion mass difference the unflavored vectors get even lighter than the flavored pseudo-Goldstones. Since one fermion mass is kept fixed while the other is incrementally increased all mesons get heavier the further we move away from degeneracy.

An important observation is that we see clearly qualitatively different behaviors. Especially, the unflavored ones do not show a (dominant) linear increase with the mass of one of the flavors. This strongly suggests that the composition of the dark hadrons changes substantially. This can have implications for decay patterns, which will be studied elsewhere [6]. Note however, that in our case even at the largest mass spitting the vector mesons remain stable.

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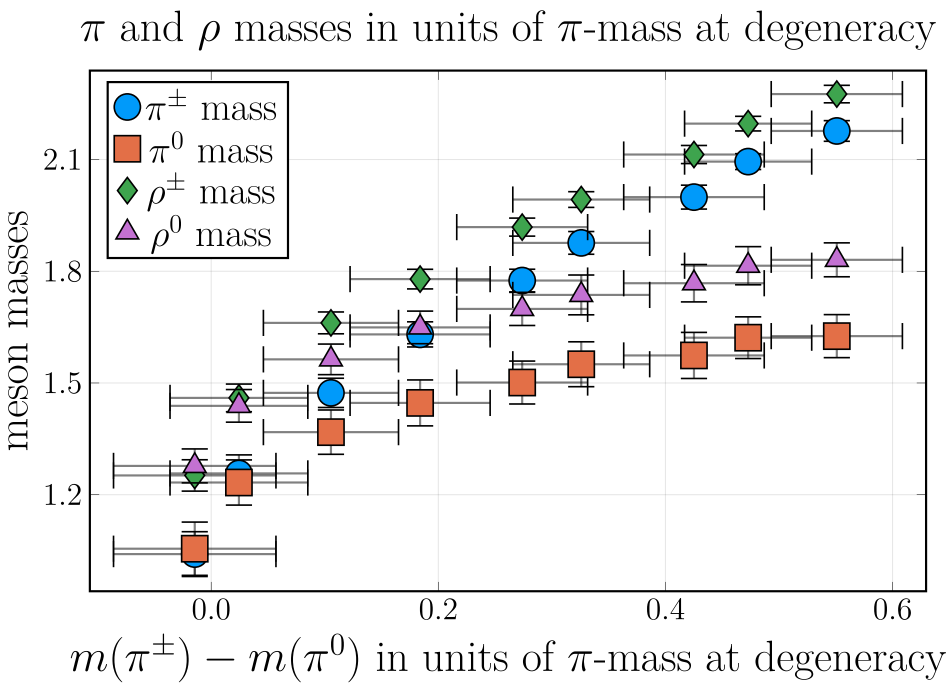

Figure 1: Masses of the flavored and unflavored Goldstone and iso-nonsinglet vector mesons masses in lattice units. The meson masses are plotted against the mass difference of the pseudo-Goldstones, which serves as a proxy for the mass-splitting on the dark quark level. At sufficiently large fermionic mass difference the unflavored vectors get even lighter than the flavored Goldstones.

5. Summary

We have studied $Sp(4)$ gauge theory with two non-degenerate massive fundamental Dirac fermions. Four of the five pseudo-Goldstone bosons remain mass-degenerate for $m_u \neq m_d$ while the unflavored one acquires a lighter mass and is therefore the lightest state in this theory.

We see strong signs for non-linear behavior, which suggests that the flavor composition of the dark hadrons changes. This can have interesting consequences for phenomenology. Also, our results show that it is possible to extract the splitting effects sufficiently well that interpolation even to tiny mass splittings, as preferred in some dark matter scenarios [14], would be accessible. A more detailed analysis of the phenomenological implications as well of lattice details is forthcoming [6].

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References

[1] Y. Hochberg, E. Kuflik, T. Volansky and J.G. Wacker, *Mechanism for Thermal Relic Dark Matter of Strongly Interacting Massive Particles*, *Phys. Rev. Lett.* **113** (2014) 171301 [1402.5143].

[2] Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky and J.G. Wacker, *Model for Thermal Relic Dark Matter of Strongly Interacting Massive Particles*, *Phys. Rev. Lett.* **115** (2015) 021301 [1411.3727].

[3] Y. Hochberg, E. Kuflik and H. Murayama, *SIMP Spectroscopy*, *JHEP* **05** (2016) 090 [1512.07917].

[4] N. Bernal, X. Chu, S. Kulkarni and J. Pradler, *Self-interacting dark matter without prejudice*, *Phys. Rev. D* **101** (2020) 055044 [1912.06681].

[5] D.A. Kosower, *SYMMETRY BREAKING PATTERNS IN PSEUDOREAL AND REAL GAUGE THEORIES*, *Phys. Lett. B* **144** (1984) 215.

[6] S. Kulkarni, A. Maas, S. Mee, M. Nikolic, J. Pradler and F. Zierler in preparation.

[7] S. Hands, P. Sitch and J.-I. Skullerud, *Hadron Spectrum in a Two-Colour Baryon-Rich Medium*, *Phys. Lett. B* **662** (2008) 405 [0710.1966].

[8] R. Lewis, C. Pica and F. Sannino, *Light Asymmetric Dark Matter on the Lattice: SU(2) Technicolor with Two Fundamental Flavors*, *Phys. Rev. D* **85** (2012) 014504 [1109.3513].

[9] E. Bennett, D.K. Hong, J.-W. Lee, C.J.D. Lin, B. Lucini, M. Piai et al., *Sp(4) gauge theory on the lattice: towards SU(4)/Sp(4) composite Higgs (and beyond)*, *JHEP* **03** (2018) 185 [1712.04220].

[10] E. Bennett, D.K. Hong, J.-W. Lee, C.J.D. Lin, B. Lucini, M. Piai et al., *Sp(4) gauge theories on the lattice: $N_f = 2$ dynamical fundamental fermions*, *JHEP* **12** (2019) 053 [1909.12662].

[11] E. Bennett, D.K. Hong, J.-W. Lee, C.-J.D. Lin, B. Lucini, M. Mesiti et al., *$Sp(4)$ gauge theories on the lattice: quenched fundamental and antisymmetric fermions*, *Phys. Rev. D* **101** (2020) 074516 [1912.06505].

[12] L. Del Debbio, A. Patella and C. Pica, *Higher representations on the lattice: Numerical simulations. SU(2) with adjoint fermions*, *Phys. Rev. D* **81** (2010) 094503 [0805.2058].

[13] A. Berlin, N. Blinov, S. Gori, P. Schuster and N. Toro, *Cosmology and Accelerator Tests of Strongly Interacting Dark Matter*, *Phys. Rev. D* **97** (2018) 055033 [1801.05805].

[14] N. Bernal, X. Chu and J. Pradler, *Simply split strongly interacting massive particles*, *Phys. Rev. D* **95** (2017) 115023 [1702.04906].