We present a lattice study of a Nambu–Jona-Lasinio (NJL) model using Wilson fermions. Four-fermion interactions are a natural part of several extensions of the Standard Model, appearing as a low-energy description of a more fundamental theory. In models of dynamical electroweak symmetry breaking they are used to endow the Standard Model fermions with masses. In infrared conformal models these interaction, when sufficiently strong, can alter the dynamics of the fixed point, turning the theory into a (near) conformal model with desirable features for model building. As a first step toward the nonperturbative study of these models, we study the phase space of the ungauged NJL model.

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I. INTRODUCTION

It has been recently shown that gauge Yukawa theories, similar to the Standard Model, even when manifestly perturbative, can abide compositeness conditions [1]. It was shown that, in certain regions of the gauge Yukawa parameter space, the Higgs-like state is not a propagating degree of freedom at high energies but a low-energy manifestation of an effective four-fermion interaction. The theory becomes at some intermediate energies a gauged manifestation of an effective four-fermion interaction. An alternative popular way to generate masses for the Standard Model fermions is known as partial compositeness [17] where each SM fermion $\Psi_{SM}$ couples linearly to a composite fermionic operator $B$ through an interaction of the form $\Psi_{SM} B$. Large anomalous dimensions of the operator $B$ (if stemming from purely fermionic fields) are then invoked such that the operator $\Psi_{SM} B$ is either super-renormalizable or marginal. Recent studies of the anomalous dimensions of conformal baryon operators in $SU(3)$ gauge theories suggest that it is hard to achieve the required anomalous dimensions in purely fermionic theories [18]. Besides the anomalously large anomalous dimensions one needs yet another level of model building to connect the composite baryons to the Standard Model fermions. The authors of Ref. [19] bypassed these hurdles by constructing a successful example of partial compositeness that makes use of both TC fermions and TC scalars. The dynamics of these theories is that large anomalous dimensions are no longer needed, one can give masses to all the fermions of the Standard Model, no new model building is required, and therefore they greatly widen the spectrum of theories to investigate on the lattice. If one insists on more involved constructions with only fermions the TC scalars can be viewed as intermediate composite states.

It is a fact that whichever is the microscopic extension of the Standard Model it will yield, in certain limits, four-fermion interactions that often reduce to the following three types:

$$ L_{\text{eff}} = \frac{a}{\Lambda_{UV}^2} (\bar{\Psi}_{SM} \Psi_{SM})^2 + \frac{b}{\Lambda_{UV}^2} \bar{\Psi}_{SM} \Psi_{SM} \bar{\Psi}_{TC} \Psi_{TC} + \frac{c}{\Lambda_{UV}^2} (\bar{\Psi}_{TC} \Psi_{TC})^2. $$

The first term, involving only Standard Model fermions, can be suppressed by the cutoff scale $\Lambda_{UV}$, while the other...
two terms may be enhanced by the dynamics of the technicolor sector.

According to Holdom [20], a model of walking dynamics with a large mass anomalous dimension can enhance the SM fermion mass term dynamically. It was later suggested [21] that walking dynamics could be achieved by having the third, Nambu–Jona-Lasinio (NJL) type, term induce chiral symmetry breaking in an otherwise infrared conformal technicolor model [21,22]. We aim therefore to study the nonperturbative dynamics of gauged NJL models.

We will ultimately study the gauged NJL model with two fermions in the adjoint representation of a SU(2) gauge group. As a first step we investigate an ungauged NJL model on the lattice with Wilson fermions. We only retain the third four-fermion term, involving only TC fermions. A similar model has been studied previously with the goal of understanding the phase structure of Wilson fermions [23–25]. Models with staggered fermions have been studied in previous works [26–30] and chiral symmetry breaking has been observed. In this study we map the phase space of the model by studying the expectation values of relevant fermion bilinears and the mass spectrum of the lightest mesonic states. The results are qualitatively similar to the mean-field model studied in [24].

This work is a necessary initial step towards a systematic study of four-fermion interactions and their impact on models of dynamical symmetry breaking.

II. THE MODEL

We study the NJL model with two flavors of fermions and two colors. The usual action of the NJL model preserves an SU(LNF) × SU(RNF) subgroup of the SU(2NF) flavor symmetry. When representing the fermion fields with pseudofermions, the action must be rendered quadratic using auxiliary fields and the fermion determinant becomes complex.3 We will therefore study a model that preserves just a U_L(1) × U_R(1) subgroup of the flavor symmetry.

The model with a nonzero quark mass is defined by the Lagrangian

\[ L(x) = \bar{\Psi}(x)(D_W + m_0)\Psi(x) + \rho^2[(\bar{\Psi}(x)\Psi(x))^2 + (\bar{\Psi}(x)i\gamma_5\lambda^3\Psi(x))^2] \]

and the equations of motion for the auxiliary fields are

\[ \langle \sigma(x) \rangle = -2\rho^2 \langle \bar{\Psi}(x)\Psi(x) \rangle, \]

\[ \langle \pi_3(x) \rangle = -2\rho^2 \langle \bar{\Psi}(x)i\gamma_5\tau_3\Psi(x) \rangle. \]

It is useful to gain insight into the model via mean-field computations [23–25]. A sketch of the phase diagram is shown in the left panel of Fig. 1 with the lattice size \(8^3 \times 16\). The right panel shows a comparison to the numerical results in the next section. The solid lines in the figure show second order transitions where the auxiliary field \(\pi_3\) develops an expectation value. Inside the region outlined by the critical lines, around \(m_0 = -4\), the expectation value \(\langle \pi_3 \rangle \neq 0\) and parity and flavor symmetries are broken. The lines also correspond to a zero pseudoscalar meson mass, and therefore to zero quark mass and the restoration of chiral symmetry.

Line 1 corresponds to the restoration of chiral symmetry in the unbroken phase. The parity broken phase below line 1 is narrow and disappears at the infinite volume limit. There is only a small change in \(\langle \sigma \rangle\) when crossing this phase. Line 2 corresponds to the critical line with spontaneously broken chiral symmetry. The parity broken phase is wider and since the model is symmetric around \(m_0 = -4\), \(\langle \sigma \rangle\) changes sign across the broken phase. The critical coupling is close to \(\gamma = 0.55a\).
III. NUMERICAL RESULTS

In order to study the model from first principles, we generate configurations of $\sigma(x)$ and $\pi_3(x)$ using the hybrid Monte Carlo (HMC) algorithm. We consider lattices of size $V = a^4 L^3 T$, with $L = 8$ and $T = 16$, except for a few simulations studying volume scaling. We use a second order integrator with trajectory length $t_{\text{HMC}} = 1$. The step size is selected so that the acceptance rate is above 0.8.

First we study the phase diagram by measuring the volume averaged expectation values of the $\pi_3$ and $\sigma$ fields. The results shown have been obtained from 100 HMC trajectories after thermalization. We choose six values of $\gamma$ from 0.4$a$ to 0.65$a$. In Fig. 2 we show their behavior at two representative values of the coupling, $\gamma = 0.4a$, which lies on the chirally symmetric side, and $\gamma = 0.6a$, which is on the broken side. The critical lines observed are also shown in the right panel in Fig. 1.

The expectation value

$$\langle \pi \rangle = \frac{1}{V} \left\langle \sum_x \pi_3(x) \right\rangle$$  \hspace{1cm} (5)

indeed becomes nonzero on lines 2 and 3. Line 1, however, is not observed from the behavior of $\langle \pi \rangle$. The expectation value is likely to be too small, or the broken phase too narrow, to be observed with the current precision. This critical line can be identified by studying the expectation value

$$\langle \sigma \rangle = \frac{1}{V} \left\langle \sum_x \sigma(x) \right\rangle.$$  \hspace{1cm} (6)

This quantity is related to the chiral condensate and has a discontinuity on line 1 if the boundary conditions for the fermion fields are periodic. The discontinuity observed at $\gamma = 0.4a$ is shown in Fig. 2 in the right panel. The measurable $\langle \sigma \rangle$ also changes behavior on the other critical

![FIG. 2. The expectation values of the auxiliary fields with varying $m_0$ and $\gamma = 0.4a$ (left) and $\gamma = 0.6a$ (middle). The plot on the right shows the region marked by dashed lines in the leftmost one. The parity broken phase is clearly marked by the nonzero expectation value of the $\pi_3$ field. The model is symmetric around $m_0 = -4$ and we see the condensate $\langle \sigma \rangle$ change sign when crossing the parity broken phase. In the zoomed plot on the right we see a small discontinuity in $\langle \sigma \rangle$, which is expected on a finite lattice when chiral symmetry is not broken.](014508-3)

![FIG. 3. The order parameter $\langle \pi \rangle$ with $\gamma = 0.6a$ on the symmetric (positive mass) side of line 2 (left) and a second order infinite volume extrapolation at $m_0 = -2.5$ (right).](014508-3)
meson and the others is encoded in a disconnected contribution in the channel, directly related to the field \( \pi_3(x) \). More details on the evaluation of the disconnected contribution are given in the Appendix. To reduce the noise in the disconnected channel of the pseudoscalar case we measure the correlator using two interpolating operators with the generalized eigenvalue method and use hopping parameter expansion in the inversion of the fermion matrix. In the case of the vector meson, the disconnected contribution does not present a problem.

For each parameter set we generate between 2000 and 20000 configurations separated by 20 HMC trajectories. Even with the large number of measurements we must note that in many cases we do not reach a plateau in the effective mass and that there may be systematic errors in the pseudoscalar masses larger than the statistical errors. The error is less than 10% and we consider our accuracy sufficient for an exploratory study of the phase diagram.

The field \( \pi_3(x) \) can also serve as an interpolating operator for the pseudoscalar meson. The evaluation of this correlation function does not require inverting the fermion matrix and is therefore efficient. We measure it using between 20000 and 100000 configurations for each parameter set separated by 10 HMC trajectories. The result is noisy at large mass and at small \( \gamma \). We report this measurement as \( m_{\pi_3} \) when it can be performed with sufficient accuracy.

It is worth noting that the diagonal pseudoscalar meson mass is not necessary for studying the phase diagram. The disconnected contribution is small in the vector correlation function and absent in the nondiagonal triplet channels. The masses of these mesons can be estimated accurately with substantially fewer data. The critical line on the chirally symmetric side (line 1) can be identified easily by finding the bare mass where all masses are zero. On the broken side these masses should remain nonzero at the critical line (line 2). Here the critical line can be identified from the expectation value \( \langle \pi \rangle \) and as long as the transition is second order, the pseudoscalar mass is zero on the critical line.

In Figs. 5, 6 and 7 we show the vector meson mass \( (m_\rho) \) and diagonal pseudoscalar mass measured from the usual fermionic correlator \( (m_\pi) \) and from the correlator of the field \( \pi_3 \) \( (m_{\pi_3}) \). We also show the order parameter for the parity broken phase \( \langle \pi_3 \rangle \). We study finite size effects by measuring the masses with lattice size 24 × 12³ at a few interesting values of \( m_0 \) and \( \gamma \). At small coupling, \( 0.4a \leq \gamma \leq 0.5a \), we see the two expected critical lines. At large \( m_0 \) the pseudoscalar and the vector masses are identical and approach zero linearly around the first critical line, line 1 in Fig. 1. On the negative mass side, the vector and pseudoscalar masses split and the pseudoscalar mass becomes zero at a second critical line, line 3 in Fig. 1. At the second critical line the model enters the wider broken parity region and we see a nonzero value for \( \langle \pi \rangle \). The difference between \( m_\rho \) and \( m_\pi \) at line 3 implies a nonzero chiral condensate.
Since the phase structure of the model can be mapped clearly and agrees well with expectation, we conclude that any systematic effects are under control. We have observed chiral symmetry breaking in the model and can distinguish between the chirally symmetric and broken phases. The next step is to include the gauge interaction and study the phase diagram of the gauged NJL model with two fermions in the adjoint representation of a $SU(2)$ gauge group.

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APPENDIX: DISCONNECTED DIAGRAMS

The Goldstone boson of spontaneous chiral symmetry breaking, the diagonal isotriplet pseudoscalar meson, differs from other pseudoscalar mesons by a disconnected term in the propagator. The term is directly related to the auxiliary field $\pi_3$ and disappears with zero four-fermion coupling. Disconnected contributions arise also in other diagonal isotriplet channels, but appear to be negligible in the vector channel.

The isotriplet meson masses are measured from correlators of the type

$$C_\Gamma(t_0) = \frac{1}{V} \langle \sum_y (\bar{\Psi}(0,0)\Gamma_a \Psi(0,0))^\dagger \Psi(y,t_0)\Gamma_a \Psi(y,t_0) \rangle$$

$$= -\frac{1}{V} \langle \sum_y \text{Tr}[(S(y,t_0;0,0)\Gamma_a)^\dagger S(0,0;y,t_0)\Gamma_a] \rangle$$

$$+ \frac{1}{V} \langle \sum_{x,y,d} \text{Tr}[S(0,0;0,0)\Gamma_a]^\dagger \text{Tr}[S(y,t_0;y,t_0)\Gamma_a] \rangle,$$

where $\tau_a$ are Pauli matrices in flavor space. The second term on the right-hand side in Eq. (A1) is called the disconnected contribution. The propagator $S$ is diagonal in flavor space and the trace is clearly zero when $a = 1, 2$. With $a = 3$ the trace becomes $\text{Tr}[S_{3,3}] = \text{Tr}[S_u - S_d]$. This can be nonzero when the pseudoscalar auxiliary field $\pi_3$ is nonzero.

Writing the propagator as

$$S_{a,d} = \frac{1}{M_{a,d}} = \frac{M_{a,d}^\dagger}{M_{a,d}^\dagger M_{a,d}}$$

$$= \sum_\mu \partial_\mu \gamma_\mu + (\sigma \pm i\pi_3 \gamma_5)$$

(A3)
the disconnected part is
\[ \text{Tr}(S_u - S_d)\Gamma = \text{Tr} \frac{2i\pi_f \gamma_5}{M^3} \Gamma. \] (A4)

At \( \gamma = 0 \) the auxiliary field \( \pi_3 \) is restricted to zero and the disconnected contribution disappears.

We observe that the disconnected term is not significant in the vector channel. This may be understood in perturbation theory around \( \gamma = 0 \): the disconnected term appears only at fourth order in \( \gamma \) in the vector channel, but arises at the second order in the pseudoscalar channel. In Fig. 8 we compare the connected and disconnected contributions in the pseudoscalar and vector channels at \( \gamma = 0.65a \), \( L = 8^3 \times 16 \) and \( m_0 = 2.9 \).

While the disconnected term appears in all diagonal isotriplet correlators, it has a different weight in different channels. The \( \Gamma = \gamma_5 \) channel mixes maximally with the \( \pi_3 \) field and has a large disconnected contribution. In the \( \Gamma = \gamma_0 \gamma_5 \) channel the contribution is somewhat smaller. In most cases we use the generalized eigenvalue method within the space of these two channels to measure the pseudoscalar meson mass. At small coupling \( \gamma = 0.4a \) and 0.45a and \( am_0 = -2.4 \), the field \( \pi_3 \) has large variation and the first channel becomes noisy. In this region we use only the second channel.


