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Composite vectorlike fermions

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ABSTRACT

We study a dynamical mechanism that generates a composite vectorlike fermion, formed by the binding of an N-tuplet of elementary chiral fermions to an N-tuplet of scalars. Deriving the properties of the composite fermion in the large N limit, we show that its mass is much smaller than the compositeness scale when the binding coupling is near a critical value. We compute the contact interactions involving four composite fermions, and find that their coefficients scale as $1/N$. Physics beyond the Standard Model may include composite vectorlike fermions arising from this mechanism.

1. Introduction

All known elementary fermions are chiral, so that their masses arise as a consequence of electroweak symmetry breaking. By contrast, vectorlike fermions have the same gauge charges for left- and right-handed components, so that their Dirac mass terms are present from the outset in the Lagrangian. Thus, it is natural to expect that vectorlike quarks or leptons, if they exist, are heavier than the Standard Model (SM) fermions. Vectorlike fermions are the subject of intensive searches at the LHC [1].

Vectorlike fermions are a key element within various strongly coupled theories for physics beyond the Standard Model (SM). Amongst these are the Top-seesaw theory [2] where a composite Higgs boson [3,4] arises from the binding of a vectorlike quark to the top quark, models where the Higgs doublet is a pseudo-Nambu–Goldstone boson (pNGB) [5,4], models of extra dimensions with bulk fermions [6,7], and Little Higgs models [8] where a vectorlike quark cancels the quadratic divergence due to the top quark. In some of these theories the vectorlike fermions are thought to be bound states, but usually there is no precise description of what are their constituents, or what is the binding interaction responsible for these composite fermion fields.

Here we study a dynamical model of composite vectorlike fermions. We start with a dimension-6 interaction between a complex scalar and an elementary chiral fermion, both transforming in the fundamental representation of a global $SU(N)$ symmetry. The dimension-6 interaction may be induced by heavy gauge boson exchange, similarly to coloron exchange [9] in top condensation models [10,11,7]. Factorizing the interaction into spin-1 auxiliary fields, which at low energy acquire kinetic terms, we find that an $SU(N)$-singlet composite Dirac fermion forms; its right- (left-) handed component is an s- (p-) wave bound state of the elementary fermion and scalar. We solve this "Composite Vectorlike Fermion" (CVF) model in the large N limit, deploying the "block-spin" renormalization group (RG) [11]. A model of this type was considered long ago [12] for describing the SM quarks and leptons as composite fields.

Near a certain critical coupling the Dirac bound state becomes much lighter than the compositeness scale. Although the Dirac mass vanishes at criticality, there is no associated chiral symmetry in this limit, due to the asymmetry between the dimension-4 and -5 operators producing the s- and p-wave components, respectively.

Large contact interactions have often been suspected of being associated with fermion compositeness [13]. Using the large-N limit of the CVF model, we compute the effective interactions involving four composite fermions, and find indeed large coefficients; however, these coefficients scale as $1/N$, and thus become perturbative for very large N.

The CVF model has features in common with the Nambu–Jona-Lasino (NJL) model [14], which describes a spin-0 bound state, composed of a right-handed fermion, and a left-handed anti-fermion. The attractive interaction which drives the formation of the bound state is a chirally-invariant 4-fermion interaction, which may be viewed as the relic of a coloron exchange [9]. The leading effects of the interaction can be treated in large-N approximation and generate a composite scalar whose mass depends upon a dimensionless coupling. As this approaches a critical value from below, the composite field becomes lighter, approaching masslessness. Above critical coupling the bound state acquires a vacuum condensate, the fermions acquire masses m_f and pNGBs appear.

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There is also a Higgs boson of mass $2m_f$ in the broken phase in the large-N approximation [10]. The analysis can be improved by use of the block-spin RG [11].

Although in the minimal CVF model the composite fermion is a gauge singlet, it is easy to give its constituents charges under the SM gauge group and to obtain composite vectorlike quarks or leptons, as often employed in theories beyond the SM. We view this CVF model as a "dynamics" which can serve as the kernel of various composite models of fermions, including partially-composite SM quarks and leptons [15] and descriptions of heavy–heavy–light baryons.

2. Composite fermion model

Consider a chiral fermion, ψ_L and a complex scalar, ϕ, which transform in the fundamental representation of a global $SU(N)$ symmetry. We postulate a Lagrangian of the form

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{\rm int}, \tag{1}$$

where the free-fields Lagrangian is

$$\mathcal{L}_0 = i\overline{\psi}_L \partial\!\!\!/ \psi_L + \partial_\mu\phi^\dagger\partial^\mu\phi - M_\phi^2\phi^\dagger\phi, \tag{2}$$

and the interaction terms are

$$\mathcal{L}_{\rm int} = -\frac{g^2}{\Lambda^2}\left(\overline{\psi}_L\gamma^\mu T^a\psi_L\right)\left(i\phi^\dagger \overleftrightarrow{\partial}_\mu T^a\phi\right). \tag{3}$$

T^a are the generators of $SU(N)$, and for the moment Λ is a momentum space cut-off on the loop integrals, with $M_\phi \ll \Lambda$. The notation in Eq. (3) is chosen to suggest that this term may be generated by the exchange of a gauge boson of coupling g and mass Λ.

Using the color Fierz identity to leading order in $1/N$,

$$T^a_{ij}T^a_{k\ell} = \frac{1}{2}\left(\delta_{i\ell}\delta_{kj} - \frac{1}{N}\delta_{ij}\delta_{k\ell}\right) \approx \frac{1}{2}\delta_{i\ell}\delta_{kj}, \tag{4}$$

Eq. (3) becomes

$$\mathcal{L}_{\rm int} \approx \frac{ig^2}{2\Lambda^2}[\overline{\psi}_L\phi]\left[(\partial\!\!\!/\phi^\dagger)\psi_L\right] + \text{H.c.} \tag{5}$$

where fields written within a pair of brackets, [...], have their $SU(N)$ indices contracted together.

The interaction term can be factorized [12] by introducing a static $SU(N)$-singlet Dirac fermion, χ, as follows:

$$\mathcal{L}_{\rm int} = \widetilde{\mathcal{L}}_{\phi\psi\chi} - \Lambda\overline{\chi}\chi + O(1/N), \tag{6}$$

where

$$\widetilde{\mathcal{L}}_{\phi\psi\chi} = i\frac{g}{\Lambda}\overline{\psi}_L(\partial\!\!\!/\phi)\chi_L - \frac{g}{2}\overline{\chi}_R\phi^\dagger\psi_L + \text{H.c.} \tag{7}$$

Integrating out χ we recover Eq. (3) in the large-N limit. Therefore, we can view Eqs. (6) and (7) as the form of the interaction at the scale Λ, which can then be evolved downward in scale to $\mu \ll \Lambda$.

Note that the choice of the couplings and mass of χ at this stage is somewhat arbitrary, due to our freedom to rescale χ_L or χ_R. Momentarily, the χ fields will develop kinetic terms which will ultimately be canonically normalized, fixing the coupling normalizations.

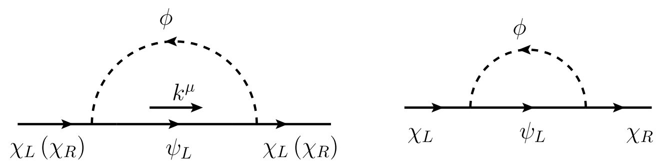

Fig. 1. Large-N contribution to the wave-function renormalizations Z_L and Z_R (left diagram), and to the Dirac χ mass (right diagram). Integration over the loop momentum k^μ, with $|k|$ cut-off at Λ, gives $\eta = 1$ in Eq. (9).

3. Low-energy effective theory

The low-energy effective Lagrangian may be derived most expeditiously by means of the block-spin RG. In the case of the NJL model, the block-spin RG has been developed in [11]. Here we view Eq. (6) as the effective Lagrangian of the theory at a mass scale Λ. To derive the effective Lagrangian at a lower scale μ, where $\Lambda > \mu > M_\phi$, we integrate out the field modes of momenta $\Lambda \geq k \geq \mu$. For the factorized CVF model of Eq. (6) this yields the effective Lagrangian at scale μ:

$$\mathcal{L}(\mu) = \mathcal{L}_0 + \widetilde{\mathcal{L}}_{\phi\psi\chi} + Z_L\overline{\chi}_L i\partial\!\!\!/\chi_L + Z_R\overline{\chi}_R i\partial\!\!\!/\chi_R - \widetilde{m}_\chi\overline{\chi}\chi, \tag{8}$$

where we neglected operators of dimension 6 or higher. The χ_R and χ_L fields have acquired kinetic terms from the first diagram of Fig. 1 (the leading-N contribution), and thus have become dynamical fields. Their wave-function renormalizations are given for $M_\phi \ll \mu$ by

$$Z_R = \frac{\kappa N}{32\pi}\ln\left(\frac{\Lambda^2}{\mu^2}\right), \qquad Z_L = \frac{\kappa N\eta}{4\pi}\left(1 - \frac{\mu^2}{\Lambda^2}\right). \tag{9}$$

The matching coefficient η, of order one, depends on the procedure of cutting off the quadratic divergence in Z_L; integrating over the loop momentum k^μ (indicated in Fig. 1), with integration limits $\mu \leq |k| \leq \Lambda$, gives $\eta = 1$. We defined the coupling constant

$$\kappa \equiv \frac{g^2}{4\pi}. \tag{10}$$

The Dirac mass of Eq. (8), arising from the second diagram of Fig. 1, is given in units of Λ by

$$\frac{\widetilde{m}_\chi}{\Lambda} = 1 - \frac{\kappa N}{8\pi}\left[1 - \frac{\mu^2}{\Lambda^2} + O\left(\frac{M_\phi^2}{\Lambda^2}\ln\left(\frac{\mu^2}{\Lambda^2}\right)\right)\right]. \tag{11}$$

It is useful to compare the NJL model side-by-side with the present scheme. First, Z_R is a conventional log-running result for an NJL type theory, *e.g.* of a composite Higgs [11]. In NJL an auxiliary scalar field, H (a Higgs field), is introduced to factorize a 4-fermion interaction, in analogy to the auxiliary fermion field χ in our CVF model. Applying the block-spin RG to the NJL model, one obtains an induced kinetic term for H with a logarithmic wave-function renormalization constant Z_H, in analogy to Z_R in Eq. (9).

The induced kinetic terms in NJL always vanish as $\mu \to \Lambda$ and this is normally referred to as the "compositeness matching conditions". The χ_R kinetic term is generated by a dimension-4 interaction, $\overline{\chi}_R\phi^\dagger\psi_L$, so that the dynamical χ_R field may be viewed as an s-wave bound state of ϕ with ψ, just as H is an s-wave bound state of $\bar{t}t$ in the top-condensation theory [11].

Second, the wave-function renormalization constant for the composite χ_L field, Z_L, has the behavior in the block-spin RG of quadratic running in scale μ, analogous to the Higgs boson mass in top condensation. It arises from two insertions of the dimension-5 vertex $\overline{\psi}_L(\partial\!\!\!/\phi)\chi_L$ (see the first diagram of Fig. 1),