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Resonant and nonresonant new phenomena of four-fermion operators for experimental searches

She-Sheng Xue [a,b,*]

[a] ICRANeT, Piazzale della Repubblica, 10-65122 Pescara, Italy
[b] Physics Department, University of Rome "La Sapienza", Rome, Italy

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ABSTRACT

In the fermion content and gauge symmetry of the standard model (SM), we study the four-fermion operators in the torsion-free Einstein–Cartan theory. The collider signatures of irrelevant operators are suppressed by the high-energy cutoff (torsion-field mass) Λ, and cannot be experimentally accessible at TeV scales. Whereas the dynamics of relevant operators accounts for (i) the SM symmetry-breaking in the domain of infrared-stable fixed point with the energy scale $v \approx 239.5$ GeV and (ii) composite Dirac particles restoring the SM symmetry in the domain of ultraviolet-stable fixed point with the energy scale $\mathcal{E} \gtrsim 5$ TeV. To search for the resonant phenomena of composite Dirac particles with peculiar kinematic distributions in final states, we discuss possible high-energy processes: multi-jets and dilepton Drell–Yan process in LHC pp collisions, the resonant cross-section in e^-e^+ collisions annihilating to hadrons and deep inelastic lepton–hadron e^-p scatterings. To search for the nonresonant phenomena due to the form-factor of Higgs boson, we calculate the variation of Higgs-boson production and decay rate with the CM energy in LHC. We also present the discussions on four-fermion operators in the lepton sector and the mass-squared differences for neutrino oscillations in short baseline experiments.

1. Introduction

The parity-violating (chiral) gauge symmetries and spontaneous/explicit breaking of these symmetries for the hierarchy of fermion masses have been at the center of a conceptual elaboration that has played a major role in donating to mankind the beauty of the SM for particle physics. The Nambu–Jona-Lasinio (NJL) model [1] of dimension-6 four-fermion operators at high energies and its effective counterpart, the phenomenological model [2] of elementary Higgs boson and its Yukawa-coupling to fermions at low energies, provide an elegant and simple description for the electroweak symmetry breaking and intermediate gauge boson masses. After a great experimental effort for many years, the ATLAS [3] and CMS [4] experiments have recently shown the first observations of a 126 GeV scalar particle in the search for the SM Higgs boson at the LHC. This far-reaching result begins to shed light on this most elusive and fascinating arena of fundamental particle physics.

In order to accommodate high-dimensional operators of fermion fields in the SM-framework of a well-defined quantum field theory at the high-energy scale Λ, it is essential and necessary to study: (i) what physics beyond the SM at the scale Λ explains the origin of these operators; (ii) which dynamics of these operators undergo in terms of their couplings as functions of running energy scale μ; (iii) associating to these dynamics where infrared (IR) or ultraviolet (UV) stable fixed point of physical couplings locates; (iv) in the domains (scaling regions) of these stable fixed points, which operators become physically relevant and renormalizable following renormalization group (RG) equations, and other irrelevant operators are suppressed by the cutoff at least $\mathcal{O}(\Lambda^{-2})$.

The strong technicolor dynamics of extended gauge theories at the TeV scale was invoked [5,6] to have a natural scheme incorporating the relevant four-fermion operator $G(\bar\psi^{ia}_L t_{Ra})(\bar t^b_R \psi_{Lib})$ of the $\langle \bar t t\rangle$-condensate model [7]. On the other hand, these relevant operators can be constructed on the basis of phenomenology of the SM at low-energies. In 1989, several authors [7–9] suggested that the symmetry breakdown of the SM could be a dynamical mechanism of the NJL type that intimately involves the top quark at the high-energy scale Λ. Since then, many models based on this idea have been studied [10]. The low-energy SM physics was supposed to be achieved by the RG equations in the domain of the IR-stable fixed point with $v \approx 239.5$ GeV [6,7,9]. In fact, the $\langle \bar t t\rangle$-condensate model was shown [11] to be energetically favorable, the top-quark

* Correspondence to: ICRANeT, Piazzale della Repubblica, 10-65122 Pescara, Italy.
E-mail address: xue@icra.it.

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and composite Higgs-boson masses are correctly obtained by solving RG equations in this IR-domain with the appropriate non-vanishing form-factor of Higgs boson in TeV scales [12,13].

Inspired by the non-vanishing form-factor of Higgs boson, the formation of composite fermions and restoration of the SM gauge symmetry in strong four-fermion coupling G [14], we preliminarily calculated the $\beta(G)$-function and showed [13] the domain of an UV-stable fixed point at TeV scales, where the particle spectrum is completely different from the SM. This is reminiscent of the asymptotic safety [15] that quantum field theories regularized at UV cutoff Λ might have a non-trivial UV-stable fixed point, RG flows are attracted into the UV-stable fixed point with a finite number of physically renormalizable operators. The weak and strong four-fermion coupling G brings us into two distinct domains. This lets us recall the QCD dynamics: asymptotically free quark states in the domain of an UV-stable fixed point and bound hadron states in the domain of a possible IR-stable fixed point.

In this Letter, we proceed a further study on this issue, distinguishing physically relevant four-fermion operators from irrelevant one in the both domains of IR- and UV-stable fixed points, and focusing on the discussion of relevant operators and their resonant and nonresonant new phenomena for experimental searches.

2. Four-fermion operators from quantum gravity

A well-defined quantum field theory for the SM Lagrangian requires a natural regularization (cutoff Λ) fully preserving the SM chiral-gauge symmetry. The quantum gravity provides a such regularization of discrete space–time with the minimal length $\tilde{a} \approx 1.2 a_{\rm pl}$ [17], where the Planck length $a_{\rm pl} \sim 10^{-33}$ cm and scale $\Lambda_{\rm pl} = \pi/a_{\rm pl} \sim 10^{19}$ GeV. However, the no-go theorem [16] tells us that there is no any consistent way to regularize the SM bilinear fermion Lagrangian to exactly preserve the SM chiral-gauge symmetry. This implies that the natural quantum-gravity regularization for the SM leads us to consider at least four-fermion operators.

It is known that four-fermion operators of the classical and torsion-free Einstein–Cartan (EC) theory are naturally obtained by integrating over "static" torsion fields at the Planck length,

$$\mathcal{L}_{EC}(e,\omega,\psi) = \mathcal{L}_{EC}(e,\omega) + \bar{\psi} e^{\mu} \mathcal{D}_{\mu} \psi + G J^d J_d, \quad (1)$$

where the gravitational Lagrangian $\mathcal{L}_{EC} = \mathcal{L}_{EC}(e,\omega)$, tetrad field $e_{\mu}(x) = e_{\mu}{}^{a}(x)\gamma_a$, spin-connection field $\omega_{\mu}(x) = \omega_{\mu}^{ab}(x)\sigma_{ab}$, the covariant derivative $\mathcal{D}_{\mu} = \partial_{\mu} - ig\omega_{\mu}$ and the axial current $J^d = \bar{\psi}\gamma^d\gamma^5\psi$ of massless fermion fields. The four-fermion coupling G relates to the gravitation-fermion gauge coupling g and basic space–time cutoff $\tilde{a}$. In the regularized and quantized EC theory [17] with a basic space–time cutoff, in addition to the leading term $J^d J_d$ in Eq. (1) there are high-dimensional fermion operators ($d > 6$), e.g., $\partial_{\sigma} J^{\mu} \partial^{\sigma} J_{\mu}$, which are suppressed at least by $\mathcal{O}(\tilde{a}^4)$.

We consider massless left- and right-handed Dirac fermions ψ_L and ψ_R carrying the SM quantum numbers, as well as right-handed Dirac sterile neutrinos ν_R and their Majorana counterparts $\nu_R^c = i\gamma_2(\nu_R)^*$. Analogously to the EC theory (1), we obtain a torsion-free, diffeomorphism and *local* gauge-invariant Lagrangian

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{EC}(e,\omega) + \bar{\psi}_{L,R} e^{\mu} \mathcal{D}_{\mu} \psi_{L,R} + \bar{\nu}_R^c e^{\mu} \mathcal{D}_{\mu} \nu_R^c \\ &\quad + G\left(J_L^{\mu} J_{L,\mu} + J_R^{\mu} J_{R,\mu} + 2 J_L^{\mu} J_{R,\mu}\right) \\ &\quad + G\left(j_L^{\mu} j_{L,\mu} + 2 J_L^{\mu} j_{L,\mu} + 2 J_R^{\mu} j_{L,\mu}\right), \quad (2)\end{aligned}$$

where we omit the gauge interactions in $\mathcal{D}_{\mu}$ and fermion flavor indexes of axial currents $J_{L,R}^{\mu} \equiv \bar{\psi}_{L,R}\gamma^{\mu}\gamma^5\psi_{L,R}$ and $j_L^{\mu} \equiv \bar{\nu}_R^c\gamma^{\mu}\gamma^5\nu_R^c$. The four-fermion coupling G is unique for all four-fermion operators and high-dimensional fermion operators ($d > 6$) are neglected. If torsion fields that couple to fermion fields are not exactly static, propagating a short distance $\tilde{\ell} \gtrsim \tilde{a}$, characterized by their large masses $\Lambda \propto \tilde{\ell}^{-1}$, this implies the four-fermion coupling $G \propto \Lambda^{-2}$.

In this article, we only discuss the relevance of dimension-6 four-fermion operators (2), which can be written as

$$+ (G/2)\left(J_L^{\mu} J_{L,\mu} + J_R^{\mu} J_{R,\mu} + j_L^{\mu} j_{L,\mu} + 2 J_L^{\mu} j_{L,\mu}\right) \quad (3)$$

$$- G\left(\bar{\psi}_L \psi_R \bar{\psi}_R \psi_L + \bar{\nu}_R^c \psi_R \bar{\psi}_R \nu_R^c\right), \quad (4)$$

by using the Fierz theorem [19]. Eqs. (3) and (4) represent repulsive and attractive operators respectively. It will be pointed out below that four-fermion operators (3) cannot be relevant and renormalizable operators of effective dimension-4 in both domains of IR and UV-stable fixed points. We will consider only four-fermion operators (4) preserving the SM gauge symmetry without the flavor-mixing of three fermion families.

3. SM gauge symmetric four-fermion operators

In the quark sector, the four-fermion operators [11]

$$G\left[(\bar{\psi}_L^{ia} t_{Ra})(\bar{t}_R^b \psi_{Lib}) + (\bar{\psi}_L^{ia} b_{Ra})(\bar{b}_R^b \psi_{Lib})\right] + \text{“terms”}, \quad (5)$$

where a, b and i, j are the color and flavor indexes of the top and bottom quarks, the quark $SU_L(2)$ doublet $\psi_L^{ia} = (t_L^a, b_L^a)$ and singlet $\psi_R^a = t_R^a, b_R^a$ are the eigenstates of electroweak interaction. The first and second terms in Eq. (5) are respectively the four-fermion operators of top-quark channel [7] and bottom-quark channel, whereas "terms" stands for the first and second quark families that can be obtained by substituting $t \to u, c$ and $b \to d, s$.

In the lepton sector, we introduce three right-handed sterile neutrinos ν_R^{ℓ} ($\ell = e, \mu, \tau$) that do not carry any SM quantum number. Analogously to Eq. (5), the four-fermion operators in terms of gauge eigenstates are,

$$G\left[(\bar{\ell}_L^i \ell_R)(\bar{\ell}_R \ell_{Li}) + (\bar{\ell}_L^i \nu_R^{\ell})(\bar{\nu}_R^{\ell} \ell_{Li}) + (\bar{\nu}_R^{\ell\, c} \nu_R^{\ell})(\bar{\nu}_R^{\ell} \nu_R^{\ell c})\right], \quad (6)$$

preserving all SM gauge symmetries, where the lepton $SU_L(2)$ doublets $\ell_L^i = (\nu_L^{\ell}, \ell_L)$, singlets ℓ_R and the conjugate fields of sterile neutrinos $\nu_R^{\ell c} = i\gamma_2(\nu_R^{\ell})^*$. Coming from the second term in Eq. (4), the last term in Eq. (6) preserves the symmetry $U_{\rm lepton}(1)$ for the lepton-number conservation, although $(\bar{\nu}_R^{\ell}\nu_R^{\ell c})$ violates the lepton number of family "ℓ" by two units. Similarly, there are following four-fermion operators

$$G\left[(\bar{\nu}_R^{\ell\, c} \ell_R)(\bar{\ell}_R \nu_R^{\ell\, c}) + (\bar{\nu}_R^{\ell\, c} u_{a,R}^{\ell})(\bar{u}_{a,R}^{\ell} \nu_R^{\ell c}) + (\bar{\nu}_R^{\ell\, c} d_{a,R}^{\ell})(\bar{d}_{a,R}^{\ell} \nu_R^{\ell c})\right], \quad (7)$$

where quark fields $u_{a,R}^{\ell} = (u,c,t)_{a,R}$ and $d_{a,R}^{\ell} = (d,s,b)_{a,R}$.

In addition, there are SM gauge-symmetric four-fermion operators that contain quark–lepton interactions [20],

$$G\left[(\bar{\ell}_L^i e_R)(\bar{d}_R^a \psi_{Lia}) + (\bar{\ell}_L^i \nu_R^e)(\bar{u}_R^a \psi_{Lia})\right] + \text{“terms”}, \quad (8)$$

where $\ell_L^i = (\nu_L^e, e_L)$ and $\psi_{Lia} = (u_{La}, d_{La})$ for the first family. The "terms" represent for the second and third families with substitutions: $e \to \mu, \tau$, $\nu^e \to \nu^{\mu}, \nu^{\tau}$, and $u \to c, t$ and $d \to s, b$. Here we do not consider baryon-number violating operators. It would be interesting to study four-fermion operators in the framework of the $SU(5)$ or $SO(10)$ unification theory.