Production at LHC of composite particles from strongly interacting elementary fermions via four-fermion operators of Einstein-Cartan type

R. Leonardi, F. Romeo, H. Sun, A. Gurrola, O. Panella, and S.-S. Xue

1INFN, Sezione di Perugia, Via A. Pascoli, I-06123, Perugia, Italy
2Department of Physics and Astronomy, Vanderbilt University, Nashville, TN, 37235, USA
3Institute of Theoretical Physics, School of Physics, Dalian University of Technology, No.2 Linggong Road, Dalian, Lianoning, 116024, P.R. China
4ICRANet, Piazzale della Repubblica, 10-65122, Pescara, Italy
5Physics Department, Sapienza University of Rome, Piazzale Aldo Moro 5, 00185 Roma, Italy

Dated: October 29, 2018

A new physics scenario shows that four-fermion operators have a strong-coupling UV fixed point, where composite fermions $F$ (bosons $\Pi$) form as bound states of three (two) SM elementary fermions and they couple to their constituents via effective contact interactions at the composite scale $\Lambda \approx O$(TeV). We present a phenomenological study to investigate such composite particles at the LHC. Using these contact interactions, we compute the production cross sections and decay widths of composite fermions in the context of the relevant experiments at LHC with pp collisions at $\sqrt{s} = 13$ TeV and $\sqrt{s} = 14$ TeV. In particular, we focus on the resonant channel $pp \rightarrow e^+ F \rightarrow e^+ e^- qq'$, whose cross section has been recently limited by the CMS Collaboration. By a simple recasting of this result, we obtain a constraint on the model parameters such that composite fermions of mass $m_F$ below 4.25 TeV are excluded for $\Lambda = m_F$. We further compute $5\sigma$ contour plots of the statistical significance and highlight the region of parameter space where $F$ can manifest using $3 < m_F < 10$ TeV and $\sqrt{s} = 13$ TeV expected by the High-Luminosity LHC. It turns out that there is a large portion of the parameter space where $F$ can be discovered and that deserve a dedicated investigation. In addition, we also study the composite boson state $\Pi_0$ with the estimation of branching ratios into two quarks (two jets) $\mathcal{B}(\Pi_0 \rightarrow qq)$ and into two boosted gauge bosons $\mathcal{B}(\Pi_0 \rightarrow GG)$, from which we obtain the branching ratios of composite-fermion decay into an electron and two boosted gauge bosons $\mathcal{B}(F \rightarrow eGG)$. Moreover we briefly discuss the possible final states of four jets or one jet with two gauge bosons in LHC $pp$ collision.

PACS numbers: 12.60.-i, 12.60.Rc, 14.80.-j

I. INTRODUCTION

The parity-violating gauge symmetries and spontaneous/explicit breaking of these symmetries for the hierarchy pattern 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 Standard Model (SM) and possible scenarios beyond SM for fundamental particle physics. A simple description is provided on the one hand by the composite Higgs-boson model of the Nambu-Jona-Lasinio (NJL) model [1] with effective four-fermion operators, and on the other by the phenomenological model of the elementary Higgs boson [2]. These two models are effectively equivalent for the SM at low energies. After a great experimental effort for many years, using $pp$ collision data at $\sqrt{s} = 7, 8$ TeV at the Large Hadron Collider (LHC), the ATLAS [3] and CMS [4] collaborations have shown the first observations of a 125 GeV scalar particle in the search for the SM Higgs boson [5, 6]. This far-reaching result begins to shed light on this most elusive and fascinating arena.

Recently, in the Run 2 of the upgraded LHC, studies on $\sqrt{s} = 13$ TeV $pp$ collision data are performed by ATLAS and CMS to search for new (beyond the SM) resonant and/or non-resonant phenomena [7–11]. These studies are continuously pushing up exclusion bounds on the parameter spaces of many possible scenarios beyond SM [12–15].

Composite-fermion scenarios have offered a possible solution to the hierarchy pattern of fermion masses [16, 17]. In this context [18–22], SM quarks “$q$” and leptons “$\ell$” are assumed to be bound states of some not yet observed fundamental constituents generically referred as preons and to have an internal substructure and heavy excited states $F$ of masses $m_F$ that should manifest themselves at the high energy compositeness scale $\Lambda$. Exchanging preons and/or binding quanta of unknown interactions between them result in effective contact interactions of SM fermions and heavy excited states. While different heavy excited states have been considered in literature [23–25], in this article we take as a reference the case of a heavy composite Majorana neutrino, $N_\ell$, for which the interaction lagrangian would be $(g_\nu/A)^2 \bar{\nu}_\mu \gamma_\mu q_L \bar{N}_\ell \gamma_\mu \ell_L$. Its theoretical studies and numerical analysis have been carefully elaborated in [26, 27]. Moreover, an experimental analysis of $\sqrt{s} = 13$ TeV $pp$ collisions at LHC of the pro-
cess \( pp \rightarrow \ell N_1 \rightarrow \ell \ell qq \) of the dilepton (dielectrons or dimuons) plus diquark final states has been carried out by the CMS collaboration [28] excluding the existence of \( N_1 \) for masses up to 4.60 (4.70) TeV at 95% confidence level, assuming \( m_{N_1} = \Lambda \).

Motivated by the theoretical inconsistency [29] of SM bilinear Lagrangian of chiral gauged fermions and quantum-gravity natural regularization, as well as by quadrilinear four-fermion operators of Einstein-Cartan type [30], an alternative physics scenario had been proposed [31, 32] on the basis of SM gauge symmetric four-fermion operators of SM left- and right-handed fermions \((\psi_L, \psi_R)\) in the charge sector “\(Q_f\)” and flavor family “\(f\)”,

\[
\sum_{f=1,2,3} G \left[ \bar{\psi}_L^f \psi_L^f \bar{\psi}_R^f \psi_R^f \right] Q_i = 0, -1/2, 1/2, -1/3.
\]

These effective operators are attributed to the new physics at the cutoff \( \Lambda_{cut} \), and reduce to the NJL-type operator for the top-quark channel. The effective coupling \( G (1) \) has two fixed points: the weak-coupled infrared (IR) fixed point and the strong-coupling ultraviolet (UV) fixed point. In the scaling domain of IR fixed point of the four-fermion coupling \( G \) at the electroweak scale \( v \approx 239.5 \) MeV, effective Operators (1) give rise to SM physics with tightly composite Higgs particle via NJL mechanism, and also offer possible solution to the hierarchy pattern of fermion masses [31, 33]. In the scaling domain of UV fixed point of the strong four-fermion coupling \( G \) at the composite scale \( \Lambda \approx \mathcal{O} \) (TeV), composite fermions (bosons) form as bound states of three (two) SM elementary fermions and they couple to their constituents via effective contact interactions [32, 34].

In the two previous scenarios, two model-independent properties are experimentally relevant for the study presented below: (i) the existence of contact interactions, in addition to SM gauge interactions, which represents an effective approach for describing the effects of the unknown internal dynamics of compositeness; (ii) the existence of composite fermions or excited states of SM fermions. For more details about the former scenario see Refs. [16–25].

In this article we study the latter scenario, focusing on the composite particles arising from four-fermion operators of Einstein-Cartan type, with massive \((m_F)\) composite fermions \( F_R^f \sim \psi_R^f (\bar{\psi}_R^f \psi_L^f) \) (bound states of three SM fermions) and massive \((m_{II})\) composite bosons \( II^f \sim (\bar{\psi}_R^f \psi_L^f) \) (bound states of two SM fermions) forming in the scaling domain of a UV fixed point of the strong four-fermion coupling \( G \) at the composite scale \( \Lambda \gtrsim 5.14 \) TeV and \( \Lambda \gtrsim m_F \gtrsim m_{II} \) [32, 35]. The effective coupling between the composite fermion (boson) and its constituents is given by the following contact interaction, which describes composite particle \( F_R^f \) (\( II^f \)) production and decay:

\[
(g_s/\Lambda)^2 \bar{\psi}_L^f \psi_R^f (\bar{\psi}^f_L \psi_R^f) F_R^f + \text{h.c.,}
\]

\[
(F_{II}/\Lambda)^2 (\bar{\psi}_R^f \psi_L^f) II^f + \text{h.c.,}
\]

where \((g_s/\Lambda)^2\) is a phenomenological parameter, and one can chose \( g_s^2 = 4\pi \) so that \( 4\pi/\Lambda^2 \) is a geometric cross-section in the order of magnitude of inelastic processes forming composite fermions (Fig. 1). Whereas, \((F_{II}/\Lambda)^2\) is the Yukawa coupling between composite boson (Fig. 2) and two fermionic constituents, and \((g_s/F_{II})^2\) relates to the form factor of composite boson. The composite fermion is in fact a bound state of a SM fermion and composite boson, namely \( F^f_R \sim \psi_R^f II^f \). The composite scale \( \Lambda > F_{II} \) can only be experimentally determined like the electroweak scale \( v \). The composite-fermion (-boson) mass \( m_F, m_{II} \propto \Lambda \) and the proportionality is of the order of unity.

In the follows we will consider the model in Eq. (1) with contact interactions of Eqs. (2) and (3) to study composite fermion production and decay at LHC and rely on the aforementioned heavy composite Majorana neutrino experimental studies [26, 27] for what concerns the determination of constraints on the model parameters. We further compute \( 5\sigma \) contour plots of the statistical significance and highlight the region of parameter space where \( F \) can manifest using 3 ab\(^{-1}\).

The article is arranged as follow. We discuss in Sec. II composite fermions’ constituents and effective contact interactions among them. Focusing on the \( e^+ e^- qq \) final state in Sec. III, the production cross sections and decay widths of these composite fermions are calculated in Sec. IV. In Sec. V we present the branching ratios of composite fermions decays in terms of selected parameters: composite scale \( \Lambda \), composite particle masses \( m_F \) and \( m_{II} \), constrained by the recast of the upper limit on \( \sigma(pp \rightarrow eeqq') \) [28] in Sec. VI. In Sec. VI we further investigate the region of the parameter space where we expect composite fermion to appear with \( 3 \text{ ab}^{-1} \), which is the statistics expected in the High-Luminosity (HL) LHC. We find out that there is a wide region of model phase space where the composite fermions can be discovered in future searches. We also discuss other channels of composite fermions in Sec. VII and, in particular, we foresee a new full hadronic final state that, to the best of our knowledge, has not been investigated at the LHC. Finally, we summarize the work with some closing remarks in Sec. VIII.

II. QUARK-LEPTON OPERATORS AND CONTACT INTERACTIONS

A. Composite fermions F

To be relevant for possible final states with leptons and quarks in ongoing high-energy experimental searches in \( pp \) collisions, we first consider, among four-fermion operators (1), the following SM gauge-symmetric and fermion-number conserving four-fermion operators,

\[
G \left[ (\bar{\ell}_L e_R) (\bar{d}_R^a \psi_{Lia}) + (\bar{\ell}_L^a \nu_R) (\bar{u}_R \psi_{Lia}) \right] + \text{h.c.,}
\]
being the SM doublet \( \ell_L = (\nu_L^c, e_L) \) and singlet \( e_R \) with an additional right-handed neutrino \( \nu_R^c \) for leptons; \( \psi_{Lia} = (u_{La}, d_{La}) \) and \( u_R^a, d_R^a \) for quarks, where the color \( a \) and SU(2)-isospin \( i \) indexes are summed over. Eq. (4) is for the first family only, as a representative of the three fermion families. The SM left- and right-handed fermions are mass eigenstates, their masses are negligible in TeV-energy regime and small mixing among three families encoded in \( G \) is also neglected [31].

In Eq. (4), each four-fermion operator has the two possibilities to form composite fermions, listed in Table I. Up to a form factor, \( E(N) \) indicates a composite fermion made of an electron (a neutrino) and a colored singlet quark pair, and its superscript for electric charge. There are four independent composite fields \( F: E_R^0, N_R^0, E_R^\pm, N_R^\pm \) and their Hermitian conjugates: \( E_L^0 = (E_R^0)\gamma_0, N_L^0 = (N_R^0)\gamma_0, E_L^\pm = (E_R^\pm)\gamma_0, N_L^\pm = (N_R^\pm)\gamma_0 \). They carry SM quantum numbers \( t_{3L}, Y, Q_L \), and \( Q_L = Y + t_{3L} \), which are the sum of SM quantum numbers \( (t_{3L}, Y, Q_L) \) of their constituents, i.e., the elementary leptons and quarks in the same SM family [32], listed in Table II, so that the contact interactions in Eq. (2) are SM gauge symmetric. The contact interactions for the production and decay of a composite fermions \( F \) are:

\[
\mathcal{L}_{CI}^F = \mathcal{V}_F + \mathcal{V}_F^\dagger,
\]

where

\[
\mathcal{V}_E = \frac{g_Y^2}{\Lambda^2} (E_L e_R)(\bar{d}_R u_{La}), \quad \text{pp or ep } \to E_L^0 e_R, \quad (6)
\]

\[
\mathcal{V}_{N^+} = \frac{g_Y^2}{\Lambda^2} (N_L^+ \nu_R^c)(\bar{u}_R^c d_{La}), \quad \text{pp or ep } \to N_L^+ \nu_R^c, \quad (7)
\]

\[
\mathcal{V}_{E^+} = \frac{g_Y^2}{\Lambda^2} (E_L^+ e_R)(\bar{d}_R^c d_{La}), \quad \text{pp or ep } \to E_L^+ e_R, \quad (8)
\]

\[
\mathcal{V}_{N^0} = \frac{g_Y^2}{\Lambda^2} (N_L^0 \nu_R^c)(\bar{u}_R^c u_{La}), \quad \text{pp or ep } \to N_L^0 \nu_R^c, \quad (9)
\]

and

\[
\mathcal{V}_{E^0}^f = \frac{g_Y^2}{\Lambda^2} (\bar{e}_L^c E_R^0)(\bar{u}_R^c d_{4aL}), \quad \text{E}_R^0 \to \bar{e}_L (\bar{u}_R^c d_{4a}) \quad (10)
\]

\[
\mathcal{V}_{N^+}^f = \frac{g_Y^2}{\Lambda^2} (\bar{\nu}_L E_R^0)(\bar{d}_R^c u_{aL}), \quad \text{N}_R^+ \to \bar{\nu}_L (\bar{d}_R^c u_{aL}) \quad (11)
\]

\[
\mathcal{V}_{E^+}^f = \frac{g_Y^2}{\Lambda^2} (\bar{e}_L^c E_R^+)(\bar{d}_R d_{4a}), \quad \text{E}_R^- \to \bar{e}_L (\bar{d}_R^c d_{4a}) \quad (12)
\]

\[
\mathcal{V}_{N^0}^f = \frac{g_Y^2}{\Lambda^2} (\bar{\nu}_L E_R^0)(\bar{u}_R^c u_{4a}), \quad \text{N}_R^0 \to \bar{\nu}_L (\bar{u}_R^c u_{4a}) \quad (13)
\]

These are relevant contact interactions for phenomenological studies of possible inelastic channels of composite-fermion production and decay in pp or ep collisions.

\section*{B. Composite bosons \( \Pi^{0,\pm} \)}

From the four-fermion interaction in Eq. (4), it is possible to form composite bosons

\[
\Pi^+ = (g^*/F\Pi)^2 (\bar{d}_R^c u_{La}), \quad \Pi^- = (\Pi^+)^\dagger \quad (14)
\]

\[
\Pi^0_d = (g^*/F\Pi)^2 (\bar{d}_R^c d_{4a}), \quad (15)
\]

\[
\Pi^0_u = (g^*/F\Pi)^2 (\bar{u}_R^c u_{4a}), \quad (16)
\]

and their Hermitian conjugates. Such normalized composite boson field has the same dimension [energy] of elementary boson field. The composite boson carries the quantum numbers that are the sum over SM quantum numbers of its two constituents, see Table III. These are pseudo composite bosons \( \Pi^{0,\pm} \), analogous to charged and neutral pions \( \pi^{0,\pm} \) in the low-energy QCD.

As shown in Fig. 2, the effective coupling between composite boson and its two constituents can be written as an effective contact interaction,

\[
\mathcal{L}_{CI}^{\Pi^{0,\pm}} = g_Y (\bar{d}_R^c u_{La}) \Pi^{0,\pm} + \text{h.c.}, \quad (17)
\]

\[
\mathcal{L}_{CI}^{\Pi^0_d} = g_Y (\bar{d}_R^c d_{4a}) \Pi^0_d + \text{h.c.} \quad (18)
\]

\[
\mathcal{L}_{CI}^{\Pi^0_u} = g_Y (\bar{u}_R^c u_{4a}) \Pi^0_u + \text{h.c.} \quad (19)
\]

where \( g_Y = (F_Y/\Lambda)^2 \). Appropriate normalizing the composite boson \( \Pi \) with the form factor \( (g^*/F\Pi)^2 \) in Eqs. (14-16), the effective contact interaction in Eqs. (17-19) can be expressed as a dimensionless Yukawa coupling \( g_Y \), whose value, corresponding to \( F_{\Pi} \) value, can be different for composite bosons in Eqs. (14-16), but we do not consider such difference here.
TABLE I. Four-fermion operators in Eq. (4) and possible composite fermions $F$ and composite bosons $\Pi$. The color $a$ index is summed.

| composite fermions $F_R$ | constituents | charge $Q_i = Y + t^3_L$ | $SU_L(2)$ 3-isospin $t^3_L$ | $U_Y(1)$-hypercharge $Y$ |
|------------------------|-------------|-------------------------|-------------------|-------------------|
| $E_R$                  | $e_R(d^R_{uL})$ | 0                       | 1/2               | $-1/2$           |
| $N_R$                  | $\nu^R_R(d^R_{dL})$ | -1                      | -1/2              | -1/2             |
| $E^0_R$                | $\nu^R_R(d^R_{dL})$ | -1                      | -1/2              | -1/2             |
| $N^0_R$                | $\nu^R_R(d^R_{dL})$ | 0                       | 1/2               | -1/2             |

TABLE II. Composite fermions $F_R$, their constituents and SM quantum numbers.

C. Contact interaction of composite fermion and boson

In the view of the composite fermion being a bound state of a composite boson and a SM fermion, using composite-boson fields in Eqs. (14-16), we rewrite $\mathcal{V}^\dagger$ in Eqs. (10-13) as follow,

$$\mathcal{V}^\dagger_{\gamma\nu} = g_\gamma(\bar{e}_LE^\mu_R)\Pi^-, \quad E^0_R \rightarrow \bar{e}_L\Pi^- \quad (20)$$
$$\mathcal{V}^\dagger_{N^+} = g_N(\bar{\nu}LN^R)\Pi^+, \quad N^0_R \rightarrow \nu_R\Pi^+ \quad (21)$$
$$\mathcal{V}^\dagger_{E^-} = g_E(\bar{e}_LE^\mu_R)\Pi^e, \quad E^0_R \rightarrow \bar{e}_L\Pi^e \quad (22)$$
$$\mathcal{V}^\dagger_{N^0} = g_N(\bar{\nu}LN^R)\Pi^0, \quad N^0_R \rightarrow \nu_R\Pi^0 \quad (23)$$

and their Hermitian conjugates $\mathcal{V}$ in Eqs. (6-9), as shown in Fig. 3. These contact interactions in Eqs. (20-23) imply that composite fermions $F$: $E^0_R$, $N^0_R$, $E^0_R$, $N^0_R$ can decay into composite bosons $\Pi^\pm$ and $\Pi^0$, which decay then to SM fermions, following the contact interactions in Eqs. (17-19) at the leading order of tree level. However, we shall consider other decay channels at the next leading order, such as neutral composite boson decay to two SM gauge bosons $\Pi^0_{u,d} \rightarrow G + \tilde{G}$.

D. Contact interaction of $\Pi^0$ composite boson and gauge bosons

Analogously to $\pi^0 \rightarrow \gamma\gamma$, the massive $\Pi^0_{u,d}$ composite boson can also decay into two gauge bosons [32]:

$$\Pi^0_{u,d} \rightarrow \gamma\gamma, \quad (24)$$
$$\Pi^0_{u,d} \rightarrow \gamma Z^0, \quad (25)$$
$$\Pi^0_{u,d} \rightarrow Z^0Z^0, \quad (26)$$
$$\Pi^0_{u,d} \rightarrow W^+W^-, \quad (27)$$

FIG. 3. We show the Feynman diagrammatic representation for the contact interaction between the composite fermion and boson, where the thin solid line represents a SM elementary fermion, the double solid line is a composite fermion and the double wave line represents a composite boson and the blob represents an interacting vertex ($F_R/A^2P_{L,R}$).

and via the contact interaction

$$\mathcal{L}^{\Pi^0}_{GG'} = \sum_{i=u,d} \frac{gg'Nc}{4\pi^2F_{H}} \varepsilon_{\mu\nu\rho\sigma}(\partial^\mu A^i)(\partial^\nu A'^{\nu})\Pi^0_{i} \quad (28)$$

where $g$ and $g'$ represent the couplings of gauge bosons $A^\mu$ and $A'^{\nu}$ to the SM quarks $u$ and $d$ with different $SU_L(2)$-isospin $i = u, d$. Actually, this effective contact interaction (28) is an axial anomaly vertex, as a result of a triangle quark loop and standard renormalization procedure in SM.

III. $e^+e^-qq'$ FINAL STATE IN $pp$ COLLISIONS

In this section we study the processes giving the $e^+e^-qq'$ final state, which we can use to set bounds on the parameters of the model by using the recast of the experimental upper limit on $\sigma(pp \rightarrow e\gamma qq')$ published in [28]. For this purpose, we consider only the case of composite fermions $F = E^0, E^0, E^+, E^-$. The detailed analysis of composite fermions $F = N^0, N^0, N^+, N^-$, giving the $\nu\nuqq'$ final states, will be considered in future.
If the energy $\sqrt{s}$ in the parton center of mass frame is larger than composite fermion masses, the resonant processes described below can occur. The virtual processes of composite fermions are not considered here. The kinematics of final states is simple in the center of mass frame of $pp$ collisions. In $pp$ collisions at LHC, the $e^+e^-qq'$ final state with this model can be obtained via the production of the composite fermions $E^0, \bar{E}^0, E^-, \bar{E}^+ \text{ in association with an electron or a positron and the subsequent decay of the composite fermion to a positron or an electron and two quarks:}$

$$pp \to e^+ E^0 \to e^+ e^- qq', \quad \text{(29)}$$
$$pp \to e^- \bar{E}^0 \to e^- e^+ qq', \quad \text{(30)}$$
$$pp \to e^+ E^- \to e^+ e^- qq', \quad \text{(31)}$$
$$pp \to e^- E^+ \to e^- e^+ qq'. \quad \text{(32)}$$

The quark-family mixing is neglected, so at parton level the previous equations are:

$$ud \to e^+ E^0 \to e^+ e^- ud, \quad \text{(33)}$$
$$\bar{u}\bar{d} \to e^- \bar{E}^0 \to e^- e^+ \bar{u}\bar{d}, \quad \text{(34)}$$
$$dd \to e^+ E^- \to e^+ e^- dd, \quad \text{(35)}$$
$$\bar{d}\bar{d} \to e^- E^+ \to e^- e^+ \bar{d}\bar{d}. \quad \text{(36)}$$

The decay of the composite fermion to a lepton and two quarks can happen directly, via the interactions in Eq. (10, 12), or with the decay of the composite fermion to a lepton and the composite boson, via the interactions in Eq. (20, 22), and the subsequent decay of the composite boson to two quarks, via the interactions in Eq. (17, 18, 19):

$$E^0 \to e^- \Pi^+ \to e^- ud, \quad \text{(37)}$$
$$\bar{E}^0 \to e^+ \Pi^- \to e^+ \bar{u}\bar{d}, \quad \text{(38)}$$
$$E^- \to e^- \Pi^0_d \to e^- dd, \quad \text{(39)}$$
$$E^+ \to e^+ \Pi^0_d \to e^+ \bar{d}\bar{d}. \quad \text{(40)}$$

The cross sections of these processes are:

$$\sigma(pp \to eF \to e^+ e^- qq') = \sigma(pp \to eF) \times B(F \to eqq'), \quad \text{(41)}$$

where

$$B(F \to eqq') = \frac{\Gamma_{\text{3-body}}(F \to eqq') + \Gamma(F \to e\Pi)B(\Pi \to qq')}{\Gamma_{\text{tot}}(F)} \quad \text{(42)}$$

and

$$\Gamma_{\text{tot}}(F) = \Gamma(F \to e\Pi) + \Gamma_{\text{3-body}}(F \to eqq'). \quad \text{(43)}$$

The total cross section of the $e^+e^-qq'$ channel from the model in $pp$ collisions is approximately given by

$$\sigma(pp \to e^+e^-qq') \approx \sigma(pp \to e^+E^0) \times B(E^0 \to e^-ud)$$
$$+ \sigma(pp \to e^-\bar{E}^0) \times B(\bar{E}^0 \to e^+ud)$$
$$+ \sigma(pp \to e^+\bar{E}^-) \times B(\bar{E}^- \to e^-dd)$$
$$+ \sigma(pp \to e^-E^+) \times B(E^+ \to e^+dd). \quad \text{(44)}$$

The calculation of these quantities will be given in the next sections.

**IV. CROSS SECTIONS AND DECAY WIDTHS**

The partonic cross section of $qq' \to eF$ is calculated by standard methods via the contact interaction in Eqs. (5-9) (all of them give the same result),

$$\hat{\sigma}(s, m_F) = \frac{1}{3 \times 64\pi} \left(\frac{g_s^2}{\Lambda^2}\right)^2 \frac{(s - m_F^2)^2}{m_F^4}, \quad \text{(45)}$$

where $\sqrt{s}$ stands for the parton center-mass-energy of $pp$ collisions in LHC experiments.

We consider the production cross sections for the composite fermions $F$ in $pp$ collisions expected at the CERN LHC collider according to Feynman’s parton model. The QCD factorization theorem allows to obtain any hadronic cross section (e.g. in $pp$ collisions) in terms of a convolution of the hard partonic cross sections $\hat{\sigma}$, evaluated at the parton center of mass energy $\sqrt{s} = \sqrt{\tau s}$, with the universal parton distribution functions $f_A(x, \hat{Q})$ which depend on the parton longitudinal momentum fractions $x$, and on the factorization scale $\hat{Q}$:

$$\sigma = \sum \int \frac{1}{\hat{Q}^2} \int \frac{1}{\tau} f_A(x, \hat{Q}^2) f_j \left(\frac{\tau}{\hat{Q}}, \hat{Q}^2\right) \hat{\sigma}(\tau s). \quad \text{(46)}$$

The factorization and renormalization scale $\hat{Q}$ is generally fixed at the value of the mass that is being produced. The parametrization of the parton distribution function is NNPDF3.0 [36] and the factorization scale has been chosen as $\hat{Q} = m_F$.

The right panel of Fig. 4 shows the agreement between analytical calculations based on Eqs. (45) and (46), for the case of the fermion $E^0$, and the results of simulations with CalcHEP where the model with four-fermion interactions has been implemented. We remark the quite
good agreement that validates our model implementation in CalcHEP.

Analytical calculations, in the similar way as the first term in Eq. (5) of Ref. [26], yield the width of composite fermion decay to its quark and lepton constituents

$$\Gamma_{3\text{-}body}(F \to eqq') = \left(\frac{g_e^2}{\Lambda^2}\right)^2 \frac{m_F^5}{4 \times (8\pi)^3}.$$  

(47)

Note that at TeV energy scales, composite fermions are massive ($m_F$) Dirac fermions, whereas all SM elementary fermions are treated as massless Dirac fermions of four spinor components, consisting of right- and left-handed Weyl fermions of two spinor components. Alternatively, the decay width $\Gamma_F$ has also been evaluated via CalcHEP, and numerical results are completely in agreement with analytical one in Eq. (47), see left panel of Figure 4.

The decay width of the composite fermion to a lepton and a composite boson $\Pi$ can easily be computed from the effective contact lagrangian in Eqs. (20) and (22):

$$\Gamma(F \to e\Pi) = \frac{1}{32\pi} \left(\frac{F_{\Pi}^2}{\Lambda^2}\right)^2 m_F \left(1 - \frac{m_{\Pi}^2}{m_F^2}\right)^2.$$  

(48)

The decay width of the $\Pi$ boson to two quarks is simply calculated by using the effective contact Lagrangian in Eq. (17) and (18),

$$\Gamma(\Pi \to qq') = \frac{3}{16\pi} \left(\frac{F_{\Pi}}{\Lambda}\right)^4 m_{\Pi}.$$  

(49)

For the $\Pi^+$ and $\Pi^-$ composite bosons this is the only decay channel, therefore composite fermions $E^0$ and $E^0$ have $B(F \to eqq') = 1$. The $\Pi_d^0$ composite boson, instead, can also decay to two gauge bosons $G\bar{G}'$, according to the contact interaction (28), the corresponding decay widths are [32]:

$$\Gamma_{\Pi_d^0 \to \gamma\gamma} = \left(\frac{5}{9}\right)^2 \Gamma,$$

(50)

$$\Gamma_{\Pi_d^0 \to \gamma Z^0} = \frac{1}{\sin^2 2\theta_W} \left(\frac{5}{2} \sin^2 \theta_W\right)^2 \Gamma,$$

(51)

$$\Gamma_{\Pi_d^0 \to Z^0 Z^0} = \frac{1}{\sin^2 2\theta_W} \left(\frac{5}{2} \sin^2 \theta_W\right)^2 \Gamma,$$

(52)

$$\Gamma_{\Pi_d^0 \to W^+ W^-} = \left(\frac{1}{8\sin^2 \theta_W}\right)^2 \Gamma,$$

(53)

where $\theta_W$ is the Weinberg angle,

$$\Gamma = \left(\frac{\alpha N_c}{3\pi F_{\Pi}}\right)^2 \frac{m_{\Pi_d^0}^3}{64\pi},$$

(54)

and the number of colors $N_c = 3$. Total decay rate $\Gamma_{\Pi_d^0 \to \gamma\gamma} + \Gamma_{\Pi_d^0 \to Z^0 Z^0} + \Gamma_{\Pi_d^0 \to W^+ W^-}$ is the sum over all contributions from Eqs. (50-53). The total $\Pi_d^0$-decay rate reads

$$\Gamma_{\sum(\Pi_d^0 \to qq')} = \Gamma(\Pi_d^0 \to \gamma\gamma) + \Gamma(\Pi_d^0 \to Z^0 Z^0) + \Gamma(\Pi_d^0 \to W^+ W^-),$$

(55)

where $\Gamma(\Pi_d^0 \to qq')$ is given by Eq. (49). Based on these results, we calculate the branching ratios of different channels in next section.

V. PARAMETERS AND BRANCHING RATIOS

In order to present the branching ratios of different possible channels in terms of parameters of the model, we are bound to discuss physically sensible parameters to explore. This model has four parameters that can be
rearranged to two dimensionless parameters for a given Λ value:

\[(\Lambda, m_F, F_{\Pi}, m_{\Pi}) \rightarrow (m_F/\Lambda, m_{\Pi}/m_F, F_{\Pi}/m_{\Pi})\].

The ratio \(m_F/\Lambda < 1\) (\(m_{\Pi}/\Lambda < 1\)) of the composite fermion (boson) mass and the basic composite scale Λ gives us an insight into the dynamics of composite fermion (boson) formation. On the other hand, a composite fermion \(F\) is composed by a composite boson and an elementary SM fermion, to represent this feature, we adopt the ratio \(m_{\Pi}/m_F < 1\) as a parameter. In addition, considering the parameters \(m_{\Pi}\) and \(F_{\Pi}\) represent the same dynamics of composite boson formation, we approximately adopt \(F_{\Pi} \approx m_{\Pi}\) so as to reduce the numbers of free parameters at this preliminary stage. As a result, for given \(\sqrt{s}\) and Λ values, we have two parameters \((m_{\Pi}/m_F, m_{\Pi}/\Lambda)\) to represent the results of cross sections, decay rates and branching ratios of various decay channels \(E \rightarrow eqq', E \rightarrow e\Pi \rightarrow eqq',\) and \(\Pi \rightarrow G\tilde{G}'\).

Figure 5 shows the branching ratios of the composite fermion \(E\) decay to \(eqq'\), i.e., \(\mathcal{B}(E \rightarrow eqq')\) of Eqs. (42,43), and \(E\) decay to \(e\Pi\),

\[\mathcal{B}(E \rightarrow e\Pi) = \Gamma(E \rightarrow e\Pi)/\Gamma_{\text{tot}}(E),\] (56)

where \(\Gamma(E \rightarrow e\Pi)\) is given by Eq. (48). The results show the direct decay channel \(E \rightarrow eqq'\) is dominant over the decay channel \(E \rightarrow e\Pi\). Note that these branching ratios are independent from \(m_F/\Lambda\) for the parameterization \(F_{\Pi} = m_{\Pi}\).

Figure 6 shows for \(F_{\Pi} = m_{\Pi}\) and two selected \(m_F/\Lambda\) values, the branching ratios of the \(\Pi_0^0\) decay to two quarks \(qq'\),

\[\mathcal{B}(\Pi_0^0 \rightarrow qq') = \Gamma(\Pi_0^0 \rightarrow qq')/\Gamma_{\text{tot}}(\Pi_0^0),\] (57)

and the \(\Pi_d^0\) decay to two gauge bosons \(\tilde{G}\tilde{G}'\),

\[\mathcal{B}(\Pi_d^0 \rightarrow \tilde{G}\tilde{G}') = \Gamma_{\text{tot}}(\Pi_d^0 \rightarrow \tilde{G}\tilde{G}')/\Gamma_{\text{tot}}(\Pi_d^0).\] (58)

The results show that the decay of \(\Pi_0^0 \rightarrow \tilde{G}\tilde{G}'\) is not negligible only for small values of both \(m_F/\Lambda\) and \(m_{\Pi}/m_F\), see Figure 6 left panel.

Figure 7 shows that the branching ratios of the direct \(E\) decay to a charged lepton and two quarks \(E \rightarrow eqq'\),

\[\mathcal{B}(E \rightarrow eqq',\text{ direct}) = \Gamma_{3\text{-body}}(E \rightarrow eqq')/\Gamma_{\text{tot}}(E),\] (59)

and indirect \(E\) decay \(E \rightarrow e\Pi \rightarrow eqq'\),

\[\mathcal{B}(E \rightarrow e\Pi \rightarrow eqq') = \frac{\Gamma(E \rightarrow e\Pi)}{\Gamma_{\text{tot}}(E)} \mathcal{B}(\Pi \rightarrow eqq'),\] (60)

and the sum of these two branching ratios gives the total branching ratio \(\mathcal{B}(E \rightarrow eqq')\) of \(E\) decay to \(eqq'\). In addition, it is also shown in Figure 7 that the branching ratio of the decay channel \(E \rightarrow e\Pi^0 \rightarrow \tilde{G}\tilde{G}'\),

\[\mathcal{B}(E \rightarrow e\Pi^0 \rightarrow \tilde{G}\tilde{G}') = \frac{\Gamma(E \rightarrow e\Pi^0)}{\Gamma_{\text{tot}}(E)} \mathcal{B}(\Pi^0_d \rightarrow \tilde{G}\tilde{G}').\] (61)

Despite this decay channel would be peculiar, having a final state signature not typical of the standard model processes, with highly energetically boosted gauge bosons plus an electron, the results show that the branching ratio \(\mathcal{B}(E^\pm \rightarrow eqq')\) is much larger than \(\mathcal{B}(E^\pm \rightarrow e\Pi^0 \rightarrow e\tilde{G}\tilde{G}')\) in the parameter space we have explored with the aforementioned parameter assumptions.

VI. BOUNDS ON THE MODEL

In this section we provide a discussion of the bounds on this model by recasting the 95% confidence level (C.L.) experimental upper limit on \(\sigma(pp \rightarrow eeqq')\) using a recent analysis [28] of 2.3 fb\(^{-1}\) data from the 2015 Run II of the LHC by the CMS collaboration with respect to the predictions of the model of composite fermions discussed in this article. Note that both electrons and positrons are collected in the final states of \(eeqq'\), electrons and positrons are not distinguished in the data analysis. For the case \(m_F = \Lambda\) one obtains that the composite fermions of this model are excluded up to masses \(m_F^\text{ex} \approx 4.25\) TeV. This result is shown in Figure 8, together with the exclusion limits \(m_F^\text{ex} \approx 3.3, 2.4, 1.5\) TeV for \(\Lambda\) fixed at 6, 9 and 12 TeV. Figure 9 shows the exclusion curve, lower (dashed) line, in the 2-dimensional parameter space \((\Lambda, m_F)\) for our model obtained via the recasting of the analysis [28] of 2.3 fb\(^{-1}\) data from the 2015 Run II of the LHC by the CMS collaboration. Here the regions of the parameter space below the curves are excluded.

We also performed a study about the potential of a dedicated analysis in the High Luminosity LHC (HL-LHC) conditions (center of mass energy of 14 TeV and luminosity of 3 ab\(^{-1}\)). We used CalcHEP to generate the processes and DELPHES [37] to simulate the detector effects. In order to separate the signal from the background, we selected events with \(p_{te_1} \geq 180\) GeV, \(p_{te_2} \geq 80\) GeV, \(p_{tj_1} \geq 210\) GeV, \(m_{ee} \geq 300\) GeV (pt...
is the transverse momentum, $e_1$ the leading electron, $e_2$ the subleading electron, $j_1$ the leading jet and $m_{ee}$ the invariant mass of the two electrons). Then we evaluated the reconstruction and selection efficiencies for signal ($\epsilon_s$) and background ($\epsilon_b$) as the ratio of the selected and the total generated events. From these efficiencies, the signal and background cross sections ($\sigma_s$, $\sigma_b$) and the integrated luminosity ($L$), it is possible to evaluate the expected number of events for the signal ($N_s$) and the SM background ($N_b$) and finally the statistical significance ($S$):

$$N_s = L \sigma_s \epsilon_s, \quad N_b = L \sigma_b \epsilon_b, \quad S = \frac{N_s}{\sqrt{N_b}}. \quad (62)$$

The $S = 5$ contour curve is shown by the upper (solid) line in Figure 9. It can be used to get indications about the potential for discovery or exclusion with the experiments at the HL-LHC, showing that there is a wide region of the model phase space where the existence of the composite fermions can be investigated; for the case $\Lambda = m_F$ we can reach masses up to $\approx 6.2$ TeV.

**VII. OTHER CHANNELS OF COMPOSITE FERMIIONS**

In this article, we have carried out the analysis of composite fermions $F = E^0, \overline{E}^0, E^+, E^-$ produced in LHC $pp$ collisions for the final states $eeqq'$ or $eeGG'$. However, the exact same analysis can be done for composite fermions $F = N^0, \overline{N}^0, N^+, N^-$ for the final state $\nu\nuqq'$ or $\nu\nuGG'$:

$$pp \rightarrow \nu N \rightarrow \nu\nuqq', \quad or \quad \nu\nuGG' \quad (63)$$

where $\nu\nu$ stands for the SM left-handed neutrino $\nu_L$ and/or sterile right-handed neutrino $\nu_R^*$. The latter is a candidate of dark-matter particles, represented by missing energy and momentum in the final states. Substituting $e^+e^-$ by $\nu_L^*\nu_R^*$ in above calculations, we obtain
and indirect $N$ decay $N \rightarrow \nu \Pi^0_u \rightarrow \nu qq'$.

$$B(N \rightarrow \nu \Pi^0_u \rightarrow \nu qq') = \frac{\Gamma(N \rightarrow \nu \Pi^0_u)}{\Gamma_{\text{tot}}(N)} B(\Pi^0_u \rightarrow qq'),$$

(65)

and the sum of these two branching ratios gives the total branching ratio $B(N \rightarrow qq')$ of $N$ decay to $\nu qq'$. The branching ratio of the decay channel $N \rightarrow \nu \Pi^0_u \rightarrow \nu GG'$,

$$B(N \rightarrow \nu \Pi^0_u \rightarrow \nu GG') = \frac{\Gamma(N \rightarrow \nu \Pi^0_u)}{\Gamma_{\text{tot}}(N)} B(\Pi^0_u \rightarrow GG'),$$

(66)

The same numerical results can be found in Fig. (7).

In fact, both composite bosons ($\Pi$) and fermions ($F$) have definite SM quantum numbers, so that the Feynman diagrammatic representations of SM perturbative gauge interactions can be easily implemented, see Eqs. (4.8)-(4.11) in Ref. [32]. However, at the leading order of contact interactions discussed in this article, all gauge interactions are neglected, except the effective contact interaction (28) of the triangle anomaly, which couples to two SM gauge bosons $GG'$. It should be mentioned that these gauge bosons $GG'$ in Eq. (28) can be two gluons that possibly fuse to a Higgs particle in the final states.

### A. Composite fermions $Q$ and four-jet final states

We further consider, among the variants of Eq. (1), the following SM gauge-symmetric and fermion-number conserving four-fermion operators of the quark sector, choosing as representative the first family [31, 32],

$$G \left[ (\bar{\psi}^c_L d_R^a) (\bar{d}_R^a \psi^c_{Lb}) + (\bar{\psi}^c_L u_R^a) (\bar{u}_R^a \psi^c_{Lb}) \right] + \text{h.c.} \).$$

(67)

Each four-fermion operator has the two possibilities to form composite fermions, listed in Table IV. Up to a certain form factor, $D$ ($U$) indicates a composite fermion made of a down quark $d$ (an up quark $u$) and a color-singlet quark pair, and its superscript for electric charge. There are four independent composite fields $Q$: $D^{2/3}_R$, $U^{-1/3}_R$, $D^{-1/3}_R$, $U^{2/3}_R$ and their Hermitian conjugates: $D^{2/3}_L$, $U^{-1/3}_L$, $D^{-1/3}_L$, $U^{2/3}_L$. They carry SM quantum numbers $t^a_3$, $y$, and $Q_i = Y + t^a_3$, which are the sum of SM quantum numbers ($t^a_3$, $Y$, $Q_i$) of their constituents, i.e., the elementary quarks in the same SM family [32], listed in Table V. These composite fermions $D$ and $U$ are analogous to the composite fermions $E$ and $N$ that have been previously analyzed.

The contact interactions for the production and decay of a composite fermions $Q$ are,

$$L'^Q_{\text{C1}} = V_Q + y^Q, \quad \text{(68)}$$
where
\[ V_{D^{-2/3}} = \frac{g^2}{\Lambda^2} (\tilde{D}_L^{a} d_R^{a}) d_R (\bar{d}_R^{a} u_L^{a}) \Rightarrow pp \rightarrow \tilde{D}_L^{a} d_R (\bar{d}_R^{a} u_L^{a}) \] (69)
\[ V_{D^{1/3}} = \frac{g^2}{\Lambda^2} (\tilde{D}_L^{a} d_R^{a}) (\tilde{u}_R^{a} d_L^{a}) \Rightarrow pp \rightarrow \tilde{U}_L^{a} d_R (\bar{d}_R^{a} u_L^{a}) \] (70)
\[ V_{U^{-1/3}} = \frac{g^2}{\Lambda^2} (\tilde{U}_L^{a} d_R^{a}) d_R (\bar{d}_R^{a} u_L^{a}) \Rightarrow pp \rightarrow \tilde{D}_L^{a} d_R (\bar{d}_R^{a} u_L^{a}) \] (71)
\[ V_{U^{1/3}} = \frac{g^2}{\Lambda^2} (\tilde{U}_L^{a} d_R^{a}) (\tilde{u}_R^{a} d_L^{a}) \Rightarrow pp \rightarrow \tilde{U}_L^{a} d_R (\bar{d}_R^{a} u_L^{a}) \] (72)
and
\[ V_{D^{2/3}} = \frac{g^2}{\Lambda^2} (\tilde{D}_L^{a} d_R^{a}) (\tilde{u}_R^{a} d_L^{a}) \Rightarrow D_R^{a} d_R (\bar{d}_R^{a} u_L^{a}) \] (73)
\[ V_{U^{-1/3}} = \frac{g^2}{\Lambda^2} (\tilde{U}_L^{a} d_R^{a}) d_R (\bar{d}_R^{a} u_L^{a}) \Rightarrow U_R^{a} (\bar{d}_R^{a} u_L^{a}) \] (74)
\[ V_{D^{-1/3}} = \frac{g^2}{\Lambda^2} (\tilde{D}_L^{a} d_R^{a}) (\tilde{d}_R^{a} d_L^{a}) \Rightarrow D_R^{a} d_R (\bar{d}_R^{a} u_L^{a}) \] (75)
\[ V_{U^{2/3}} = \frac{g^2}{\Lambda^2} (\tilde{U}_L^{a} d_R^{a}) (\tilde{u}_R^{a} d_L^{a}) \Rightarrow U_R^{a} (\bar{d}_R^{a} u_L^{a}) \] (76)

These are the relevant contact interactions for phenomenological studies of possible inelastic channels of composite-fermion $Q = (D, U)$ production and decay in $pp$ collision. Without considering SM gauge interactions and family mixings, the phenomenological analysis and results are the same as those of composite fermions $(E, N)$, apart from different final states.

### B. Possible Q-resonances and four jets final states in pp collisions

The $pp$ or $ep$ collisions produce a composite fermion $Q$ and a quark $q = u, d$, i.e., the production process $pp \rightarrow Qq$ via the contact interactions in Eq. $V_Q$ (69-72). The composite fermions $Q$ decay to a quark and a pair of quarks, $Q \rightarrow q\bar{q}q$ via the contact interactions $Y_Q$ (73-76).

A composite fermion $Q = D^{2/3}_R, U^{-1/3}_R, D^{-1/3}_R, U^{2/3}_R$ appears in the $s$-channel as a resonance. The following final states are foreseen in $pp$ collisions at LHC:

\[ pp (u\bar{d}) \rightarrow \tilde{d}D^{2/3} \rightarrow \tilde{d} + d + 2\text{ jets (}u\bar{d}), \] (77)
\[ pp (d\bar{d}) \rightarrow \tilde{d}D^{-1/3} \rightarrow d + \bar{d} + 2\text{ jets (}d\bar{d}), \] (78)
\[ pp (d\bar{u}) \rightarrow \tilde{u}U^{-1/3} \rightarrow \tilde{u} + u + 2\text{ jets (}d\bar{u}), \] (79)
\[ pp (u\bar{u}) \rightarrow \tilde{u}U^{2/3} \rightarrow \tilde{u} + u + 2\text{ jets (}u\bar{u}). \] (80)

These four-jet events $pp \rightarrow jj + jj$ have a simple, but peculiar kinematic distribution that may be easily identified from background. At the present tree-level approximation of contact interactions, the cross sections, decay rates, kinematics and parameters $(\Lambda, m_F)$ are the same as those of $pp \rightarrow \ell\ell + jj$ processes.

Analogously to the branching ratios (61) and (66) of the decay channels $E \rightarrow e \Pi \Xi \rightarrow e \tilde{G} \tilde{G}'$ and $N \rightarrow \nu \Pi \Xi \rightarrow \nu \tilde{G} \tilde{G}'$, we can obtain the branching ratios of composite fermions $D^{-1/3}$ and $U^{2/3}$ decay into a quark (jet) and two boosted gauge bosons,

\[ B(D^{-1/3} \rightarrow d\Pi \Xi \rightarrow d \tilde{G} \tilde{G}') = \frac{\Gamma(D^{-1/3} \rightarrow d\Pi \Xi)}{\Gamma_{\text{tot}}(D^{-1/3})} \times B(\Pi \Xi \rightarrow \tilde{G} \tilde{G}'); \] (81)
\[ B(U^{2/3} \rightarrow u\Pi \Xi \rightarrow u \tilde{G} \tilde{G}') = \frac{\Gamma(U^{2/3} \rightarrow u\Pi \Xi)}{\Gamma_{\text{tot}}(U^{2/3})} \times B(\Pi \Xi \rightarrow \tilde{G} \tilde{G}'). \] (82)

At the present tree-level approximation of contact interactions, the cross sections, decay rates, branching ratios, kinematics and parameters $(\Lambda, m_F)$ of the composite fermions $D^{-1/3}$ and $U^{2/3}$ production and decay into a jet and two boosted gauge bosons are the same as those of the composite fermions $E \pm$ and $N$ production and decay into a lepton and two boosted gauge bosons discussed in Eqs. (61) and (66).
Here again we neglect the small contributions from perturbative SM gauge interactions, and only consider the dominant tree-level contributions of the first-family contact interactions (68) without any flavor mixing. Other possible channels with final states of gauge and Higgs bosons, as well as heavy quarks \[32, 35\] are expected to have much smaller branching ratios and will be duly discussed and analyzed in future.

VIII. SUMMARY AND REMARKS

In the weak coupling regime the effective four-fermion operators of NJL-type possess an IR-fixed point, rendering the elegant Higgs mechanism of the SM of particle physics at low energies. In the strong coupling regime, on the other end, these operators could possess an UV-fixed point, giving rise to composite fermions/bosons composed by SM fermions and their relevant contact interactions with SM fermions at high energies $O(\text{TeV})$. Using the first SM family, we study the spectra of composite particles and contact interactions in quark-lepton and quark-quark sectors. The cross sections and decay rates of composite particles are calculated to study their phenomenologies based on the LHC physics from $pp$ collision at high energy TeV scale. In particular, the processes giving $e^+e^-qq'$ final state are analyzed by using the recast of the experimental upper limit on $\sigma(pp \rightarrow eeqq')$ to set bounds on the parameters of composite particles and their contact interactions. We determine that a composite fermion, $(F)$, of mass $m_F$ below 4.25 TeV can be excluded for $\Lambda = m_F$. At the same time, we compute $3\sigma$ and $5\sigma$ contour plots of the statistical significance and highlight the phase space in which $F$ can manifest using $3 \text{ab}^{-1}$, foreseen at the high luminosity LHC (HL-LHC). This result shows that there is a vast range of model parameters to which a dedicated search can be sensitive to $F$ composite fermions and we thus encourage such efforts in future investigations at the LHC. Moreover, we further consider other decay channels of composite fermions and, in particular, we find that the case of $Q$-resonances can lead to a four jets final state (a triplet of jets produced in association with another jet). This signature, to the best of our knowledge, has escaped the realm of the searches at the LHC and can offer a new possibility to search for composite fermions and physics beyond the SM. The detailed phenomenology of the $Q$-resonances is the subject of an ongoing work. The phenomenology of two boosted SM gauge bosons Eqs. (58,61,66,81,82), and two gluons fusing into a Higgs boson in final states of composite boson and fermion decays will be further studied.

It is an interesting question to see how these phenomenologies can possibly account for some recent results obtained in both space and underground laboratories. The cosmic rays $pp$ collisions produce composite particles $E$ that decay into electrons and positrons. This may explain an excess of cosmic ray electrons and positrons around TeV scale \[38, 39\]. In addition, recent AMS-02 results \[40\] show that at TeV scale the energy-dependent proton flux changes its power-law index. This implies that there would be “excess” TeV protons whose origin could be also explained by the resonance of composite fermions $N$ due to the interactions of dark-matter and normal-matter particles. These composite fermions should appear as resonances by high-energy sterile neutrinos inelastic collisions with nucleons (xenon) at the largest cross-section, then resonances decay and produce some other detectable SM particles in underground laboratories \[41\]. Similarly, in the ICECUBE experiment \[42\], we expect events where the neutrinos change their directions (lower their energies) by their inelastic collisions to form the resonances of composite fermions $N$ at a high energy scale ($\approx \text{TeV}$). Similarly to the analogy between the Higgs mechanism and BCS superconductivity, the composite-particle counterparts in condensed matter physics have been recently discussed \[43\].

IX. ACKNOWLEDGEMENTS

The work of Alfredo Gurrola and Francesco Romeo is supported in part by NSF Award PHY-1806612. The work of Hao Sun is supported by the National Natural Science Foundation of China (Grant No.11675033).

[1] Y. Nambu and G. Jona-Lasinio, Phys. Rev. 122 (1961) 345.
[2] F. Englert, R. Brout, Phys. Rev. Lett. 13 (1964) 321; P. W. Higgs, Phys. Lett. 12 (1964) 132; Phys. Rev. Lett. 13 (1964) 508; Phys. Rev. 145 (1966) 1156; G. S. Guralnik, C. R. Hagen, T. W. B. Kibble, Phys. Rev. Lett. 13 (1964) 585; and T. W. B. Kibble, Phys. Rev. 155 (1967) 1554.
[3] ATLAS Collaboration, JINST 3 (2008) S08003
[4] CMS Collaboration, JINST 3 (2008) S09004
[5] ATLAS Collaboration, Phys. Lett. B 716 (2012) 1, and http://atlas.ch/.
[6] CMS Collaboration, Phys. Lett. B 716 (2012) 30-61.
[7] M. Aaboud et al. [ATLAS Collaboration], JHEP 1609, 001 (2016) doi:10.1007/JHEP09(2016)001 [arXiv:1606.03833 [hep-ex]].
[8] V. Khachatryan et al. [CMS Collaboration], Phys. Rev. Lett. 117, no. 5, 051802 (2016) doi:10.1103/PhysRevLett.117.051802 [arXiv:1606.04093 [hep-ex]].
[9] G. Aad et al. (ATLAS Collaboration), Phys. Rev. D 87, 015010 (2013).
[10] V. Khachatryan et al. [CMS Collaboration], Eur. Phys. J. C 76, no. 5, 237 (2016) doi:10.1140/epjc/s10052-016-4067-z [arXiv:1601.06431 [hep-ex]].
[11] G. Aad et al. [ATLAS Collaboration], JHEP 1512, 055 (2015) doi:10.1007/JHEP12(2015)055 [arXiv:1506.00962 [hep-ex]].

[12] V. Khachatryan et al. [CMS Collaboration], Phys. Rev. D 91, no. 5, 052009 (2015) doi:10.1103/PhysRevD.91.052009 [arXiv:1501.04198 [hep-ex]].

[13] V. Khachatryan et al. [CMS Collaboration], JHEP 1408, 173 (2014) doi:10.1007/JHEP08(2014)173 [arXiv:1405.1994 [hep-ex]].

[14] G. Aad et al. [ATLAS Collaboration], Phys. Rev. Lett. 115, no. 13, 131801 (2015) doi:10.1103/PhysRevLett.115.131801 [arXiv:1506.01081 [hep-ex]].

[15] V. Khachatryan et al. [CMS Collaboration], JHEP 1506, 121 (2015) doi:10.1007/JHEP06(2015)121 [arXiv:1504.03198 [hep-ex]].

[16] J.C. Pati, A. Salam, J.A. Strathdee, Are quarks composite?, Phys. Lett. B 59 (1975) 265, https://doi.org/10.1016/0370-2693(75)90042-8; H. Harari, Composite models for quarks and leptons, Phys. Rep. 104 (1984) 159, https://doi.org/10.1016/0370-1573(84)90207-2; O.W. Greenberg, C.A. Nelson, Composite models of leptons, Phys. Rev. D 10 (1974) 2567, https://doi.org/10.1103/PhysRevD.10.2567.

[17] P.A. M. Dirac, Scientific American 208, 45 (1963).

[18] H. Terazawa, K. Akuma, and Y. Chikashige, Phys. Rev. D15, 480 (1977).

[19] H. Terazawa, Phys. Rev. D22, 184 (1980).

[20] E. Eichten and K. Lane, Physics Letters B 90, 125 (1980).

[21] E. Eichten, K. D. Lane, and M. E. Peskin, Phys. Rev. Lett. 50, 811 (1983).

[22] H. Terazawa, in EUROPHYICS TOPICAL CONFERENCE: FLAVOR MIXING IN WEAK INTERACTIONS ERICE, ITALY, MARCH 4-12, 1984 (1984).

[23] N. Cabibbo, L. Maiani, and Y. Srivastava, Phys. Lett. B139, 459 (1984).

[24] U. Baur, M. Spira, and P. M. Zerwas, Phys. Rev. D 42, 815 (1990).

[25] U. Baur, I. Hinchliffe, and D. Zeppenfeld, Int. J. Mod. Phys. A2, 1285 (1987).

[26] R. Leonardi, O. Panella, and L. Fanò, Doubly charged heavy leptons at LHC via contact interactions, Phys. Rev. D 90, 035001, (2014).

[27] R. Leonardi, L. Alunni, F. Romeo, L. Fanò, O. Panella, Hunting for heavy composite Majorana neutrinos at the LHC Eur. Phys. J. C76 (2016) no.11, 593, arXiv:1510.07988.

[28] The CMS Collaboration, “Search for a heavy composite Majorana neutrino in the final state with two leptons and two quarks at $\sqrt{s} = 13$ TeV”, Phys. Lett. B 775, 315 (2017) arXiv:1706.08578.

[29] H. B. Nielsen and M. Ninomiya, Nucl. Phys. B 185 (1981) 20 [Erratum ibid. B 195 (1982) 541]; Phys. Lett. B 105 (1981) 219; Int. J. Mod. Phys. A 6 (1991) 2913.

[30] S.-S. Xue, “Quantum Regge calculus of Einstein-Cartan theory”, Phys. Lett. B 682 (2009) 300,[arXiv:0902.3407]; “Detailed discussions and calculations of quantum Regge calculus of Einstein-Cartan theory”, Phys. Rev. D 82 (2010) 064039 [arXiv:0912.2435]; “The phase structure of Einstein-Cardan theory”, Phys. Lett. B 665 (2008) 54 [arXiv:0804.4619]; “The Phase and Critical Point of Quantum Einstein-Cartan Gravity”, Phys. Lett. B 711 (2012) 404 [arXiv:1112.1323].

[31] S.-S. Xue, JHEP 11 (2016) 072, arXiv:1605.01266. For more details, see Refs. [33].

[32] S.-S. Xue, JHEP 05(2017)146, arXiv:1601.06845. For more details, see Refs. [34].

[33] S.-S. Xue, Phys. Rev. D93, 073001 (2016), arXiv:1506.05994; Phys. Lett. B 721 (2013) 347, arXiv:1301.4254; Mod. Phys. Lett. A, Vol. 14 (1999) 2701, ibid Vol.15 (2000) 1089; Phys. Lett. B 398 (1997) 177; ibid B224, (1989) 309; B249, (1990), 565; Z. Phys. C 50, (1991) 15; Nuovo Cimento A, 105 (1992) 131; ibid 105 (1992) 1225; Nucl. Phys. B (Proc. Suppl.) 53 (1997) 688, ibid 63A-C (1998) 596, ibid 94 (2001) 781; The proceedings of international workshop “Mass and Mixings of Quarks and Leptons”, Shizuoka, Japan, March 19-21, 1997, Edited by Yoshiho Koide G. Preparata and S.-S. Xue, Phys. Lett. B 264 (1991) 35, Phys. Lett. B 302 (1993) 442; B325 (1994) 161-165; B377 (1996) 124-128.

[34] S.-S. Xue, Phys. Lett. B 381, 277 (1996), Nucl. Phys. B 486, 282 (1997), ibid 580, 365 (2000); Phys. Rev. D 61, 054502 (2000), ibid 64, 094504 (2001); J. Phys. G, Nucl. Part. Phys. 29 (2003) 2381; Phys. Lett. B 706 (2011) 213; ibid 665 (2008) 54; https://arxiv.org/abs/hep-lat/0006024.

[35] S.-S. Xue, Phys. Lett. B374 (2014) 172 (arXiv:1405.1867); ibid B744 (2015) 88 (arXiv:1501.06844); B727 (2013) 308 (arXiv:1308.6486).

[36] R. D. Ball et al. [NNPDF Collaboration], JHEP 1504 (2015) 040 doi:10.1007/JHEP04(2015)040 [arXiv:1410.8849 [hep-ph]].

[37] J. de Favereau et al., JHEP 1402, 057 (2014).

[38] See for example, J. Chang, et al. Nature Vol 456—20 Nov. 2008; Y-Z. Fan, B. Zhang and J. Chang, JIMPD Vol. 19, (2010) 2011.

[39] N. Arkani-Hamed, D. P. Finkelstein, T. Slatyer, and N. Weiner, Phys. Rev. D 79, 015014 (2009); Dmitry Malyshev, Ilias Cholis, and Joseph Gelfand, Phys. Rev. D80, 063005 (2009).

[40] AMS collaboration, Phys. Rev. Lett. 114, 171103 (2015).

[41] https://www.lngs.infn.it/en and http://pandax.physics.sjtu.edu.cn/.

[42] https://icecube.wisc.edu/.

[43] H. Kleinert and S-S. Xue, “Composite Fermions and their pair states in a Strongly-Coupled Fermion Liquid”, Nuclear Physics B 936 (2018) 352-363, https://arxiv.org/abs/1708.04023.