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Elementary particle mass generation without Higgs

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We discuss how a recently discovered non-perturbative field-theoretical mechanism giving mass to elementary fermions can be extended to generate a mass for the electro-weak bosons, when weak interactions are introduced, and can thus be used as a viable alternative to the Higgs scenario. We will show that this new scheme offers a solution of the mass naturalness problem, an understanding of the fermion mass hierarchy and a physical interpretation of the electro-weak scale.

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1. Introduction

In ref. [1] (see also ref. [2] for some preliminary results) a field-theoretical renormalizable model was introduced where an SU(2) fermion doublet, subjected to non-abelian gauge interactions of the QCD type, is coupled to a complex scalar field via a $d = 4$ Yukawa term and an "irrelevant" $d > 4$ Wilson-like operator. Despite the fact that both terms break chiral invariance, one can show that there exists a critical value of the Yukawa coupling where chiral symmetry is recovered, up to effects that vanish as the UV cut-off is removed. The interesting observation is that in the Nambu–Goldstone (NG) phase of the critical theory non-perturbative (NP) $\mathrm{O}(\Lambda_{\mathrm{RGI}})$ masses for elementary fermions get dynamically generated. This feature was confirmed by numerical simulations in ref. [3].

Fermion masses emerge from a sort of "interference" between residual UV chiral breaking terms and NP effects, coming from the spontaneous breaking of the (recovered) chiral symmetry (S$\tilde{\chi}$SB) occurring in the NG phase of the theory. S$\tilde{\chi}$SB is a phenomenon that is standardly induced by strong interaction dynamics. A detailed analysis of this remarkable field-theoretical mass generation mechanism shows that the NP fermion masses have the parametric form

$$m_f \sim C_f(\alpha)\Lambda_{\mathrm{RGI}}\,, \tag{1}$$

where Λ_{RGI} is the RGI scale of the theory and $C_f(\alpha)$ is a function of the gauge coupling constants $\{\alpha\}$ of the theory. If we take the irrelevant chiral breaking Wilson-like term to be a $d = 6$ operator, one finds at the lowest loop order $C_f(\alpha) = \mathrm{O}(\alpha_f^2)$, where α_f is the coupling constant of the strongest among the gauge interactions the particle is subjected to.

A far reaching consequence of the formula (1), if applied to the top quark, is that owing to $m_{top} = \mathrm{O}(\Lambda_{\mathrm{RGI}})$, to match its experimental value a new sector of super-strongly interacting particles, gauge-invariantly coupled to standard matter, needs to exist in order for the full theory, including the new sector and Standard Model (SM) particles, to have an RGI scale $\Lambda_{\mathrm{RGI}} \equiv \Lambda_T \gg \Lambda_{QCD}$ and of the order of a few TeV's. We immediately notice that the reason for assuming the existence of a super-strongly interacting sector here is very different from the reason why Technicolor was introduced [5, 6]. Technicolor was invoked to give mass to the electro-weak (EW) bosons in the first place, while in the present approach super-strong interactions are introduced to give the right order of magnitude to the mass of the top quark and the W (see eq. (2) below). Anyway, to avoid confusion and following Glashow [7], we will refer to this new set of particles as Tera-particles.

The model of ref. [1] can be naturally extended to incorporate EW interactions and leptons [8–11]. EW bosons as well as leptons will acquire NP masses $\mathrm{O}(\Lambda_T)$ via the same mechanism that leads to eq. (1) [1], but with coefficient functions that scale like powers of the EW gauge couplings. E.g. at the leading loop order one gets for the W mass the parametric expression (see sect. 2)

$$M_W \sim \sqrt{\alpha_w}c_w(\alpha)\Lambda_{\mathrm{RGI}}\,, \quad c_w(\alpha) = \mathrm{O}(\alpha)\,, \tag{2}$$

where g_w is the weak coupling and α is a short-hand for the set of couplings $[\alpha_s, \alpha_T]$ with α_s and α_T the strong and Tera-strong gauge couplings, respectively.

Eqs. (1) and (2) are somewhat similar to the expression of the Higgs-masses of fermions and W's with, however, two fundamental differences. The first is that the scale of the masses is not the vev of the Higgs field, but a dynamical scale related to a new interaction. The second is that the

[1]With the SM hypercharge assignment, neutrinos are massless because in this model ν_R is sterile.

modulation of the Yukawa couplings that in the SM is introduced by hand to fit the values of fermion masses, here is controlled by computable coefficients whose leading behaviour is determined by the magnitude of the gauge coupling of the strongest among the interactions the particle feels.

We conclude from this analysis that the NP scenario for mass generation we are advocating can be considered as a valid alternative to the Higgs mechanism, with the extra major advantage that we do not have to deal with tuning problems related to the Higgs mass as there is no Higgs around. A further conceptual bonus is that the EW scale can be naturally interpreted as (a fraction of) the dynamical parameter, Λ_T. Moreover, the dependence of the NP fermion masses upon the gauge couplings (at the lowest loop order one finds $C(\alpha_f) = \mathrm{O}(\alpha_f^2)$ for a $d = 6$ Wilson-like operator, see eq. (7) below) offer a hint to understand the fermion mass hierarchy $m_{tau} \ll m_{top} \ll m_{Tera}$, as due to the ranking among weak, strong and Tera-strong gauge couplings, $\alpha_Y \ll \alpha_s \ll \alpha_T$. We expect the gauge coupling dependence of the NP fermion mass estimate (1) to be more compelling for the heaviest of the SM fermion families, which we then assume the following analysis refers to.

There is a couple of further interesting features of the approach we are describing that are worth mentioning, but which we are not going to develop in this talk. First of all, lacking (the need for) a Higgs boson, the 125 GeV resonance, recently identified at LHC, is interpreted as a W^+W^-/ZZ composite state, bound by Tera-particles exchanges. Since this state is light on the Λ_T scale, it should be incorporated in the low energy effective Lagrangian (LEEL) obtained by integrating out the "heavy" Tera-degrees of freedom. One finds that the LEEL of the model, valid at $(\text{momenta})^2 \ll \Lambda_T^2$, resembles very much the SM Lagrangian [10]. Secondly it was shown in ref. [12] that with a reasonable choice of the elementary particle content, a theory extending the SM with the inclusion of the new Tera-sector leads to gauge coupling unification at a $\sim 10^{18}$ GeV scale.

2. Introducing weak and Tera-interactions

Based on the results of ref. [1] in order to proceed to the construction of a possible, realistic beyond-the-SM-model we need to introduce weak interactions. At the same time, as mentioned in the Introduction, it is necessary to extend the model by incorporating a super-strongly interacting sector, in order for the whole theory to have an RGI scale, $\Lambda_T \gg \Lambda_{QCD}$ and of the order of a few TeV's. Only in this way there is the chance that eq. (1) can yield the correct order of magnitude of the top quark mass. As proved in [10], the extended Lagrangian is obtained by doubling the structure of quarks in order to encompass Tera-particles (Q=Tera-quarks and G=Tera-gluons) and gauging an exact global left symmetry to introduce weak interactions. The whole Lagrangian reads

$$\mathcal{L}(q,Q;\Phi;A,G,W) = \mathcal{L}_{kin}(q,Q;\Phi;A,G,W) + \mathcal{V}(\Phi) + \mathcal{L}_{Yuk}(q,Q;\Phi) + \mathcal{L}_{Wil}(q,Q;\Phi;A,G,W) \tag{3}$$

$$\bullet\, \mathcal{L}_{kin}(q,Q;\Phi;A,W) = \frac{1}{4}\Big(F^A\cdot F^A + F^G\cdot F^G + F^W\cdot F^W\Big) +$$
$$+\Big[\bar q_L \mathcal{D}\!\!\!/^{AW} q_L + \bar q_R \mathcal{D}\!\!\!/^{A} q_R\Big] + \Big[\bar Q_L \mathcal{D}\!\!\!/^{AGW} Q_L + \bar Q_R \mathcal{D}\!\!\!/^{AG} Q_R\Big] + \frac{k_b}{2}\mathrm{Tr}\,[(\mathcal{D}^W_\mu\Phi)^\dagger \mathcal{D}^W_\mu\Phi] \tag{4}$$

$$\bullet\, \mathcal{V}(\Phi) = \frac{\mu_0^2}{2} k_b \mathrm{Tr}\,[\Phi^\dagger\Phi] + \frac{\lambda_0}{4}(k_b\mathrm{Tr}\,[\Phi^\dagger\Phi])^2 \tag{5}$$

$$\bullet\, \mathcal{L}_{Yuk}(q,Q;\Phi) = \eta_q\,(\bar q_L\Phi\, q_R + \bar q_R\Phi^\dagger q_L) + \eta_Q\,(\bar Q_L\Phi\, Q_R + \bar Q_R\Phi^\dagger Q_L) \tag{6}$$

$$\bullet\, \mathcal{L}_{Wil}(q,Q;\Phi;A,G,W) = \frac{b^2}{2}\rho_q\,(\bar q_L \overleftarrow{\mathcal{D}}^{AW}_\mu \Phi \mathcal{D}^A_\mu q_R + \bar q_R \overleftarrow{\mathcal{D}}^{A}_\mu \Phi^\dagger \mathcal{D}^{AW}_\mu q_L) +$$
$$+\frac{b^2}{2}\rho_Q\,(\bar Q_L \overleftarrow{\mathcal{D}}^{AGW}_\mu \Phi \mathcal{D}^{AG}_\mu Q_R + \bar Q_R \overleftarrow{\mathcal{D}}^{AG}_\mu \Phi^\dagger \mathcal{D}^{AGW}_\mu Q_L)\,. \tag{7}$$

The Lagrangian (3) enjoys an exact global symmetry, $\chi_L \times \chi_R$, acting on fermion, W's and scalar fields, that protects elementary particle masses against quantum power divergencies. Besides the Yukawa (eq. (6)) and the Wilson-like (eq. (7)) operators, also the kinetic term of the scalar (last term in eq. (4)) fails to be invariant under the "restricted chiral" transformations $\tilde{\chi}_L \times \tilde{\chi}_R$ acting on fermions and W's only, and mixes with them [10]. Thus to get a theory invariant under the chiral $\tilde{\chi}_L \times \tilde{\chi}_R$ trasformations, on top of η_q and η_Q, a further parameter, k_b, is introduced that needs to be tuned. The conditions determining such "critical" theory correspond to have at the level of the Quantum Effective Lagrangian (QEL) vanishing effective Yukawa interactions and no kinetic term for the scalar field.

In the Wigner phase the tuning conditions that determine the critical values, $\eta_{q\,cr}$, $\eta_{Q\,cr}$ and $k_{b\,cr}$, imply the cancellations schematically indicated in fig. 1. At the lowest loop order one finds

$$\eta_{q\,cr}^{(1-loop)} = \rho_q\,\eta_{1q}\alpha_s\,, \qquad \eta_{Q\,cr}^{(1-loop)} = \rho_Q\,\eta_{1Q}\alpha_T\,, \qquad k_{b\,cr}^{(1-loop)} = [\rho_q^2 N_c + \rho_Q^2 N_c N_T]k_1\,, \tag{8}$$

with η_{1q}, η_{1Q} and k_1 computable coefficients and SU(N_T) the Tera-gauge group. The key observation here is that UV power loop divergencies are exactly compensated by the IR behaviour of the inserted Wilson-like vertices.

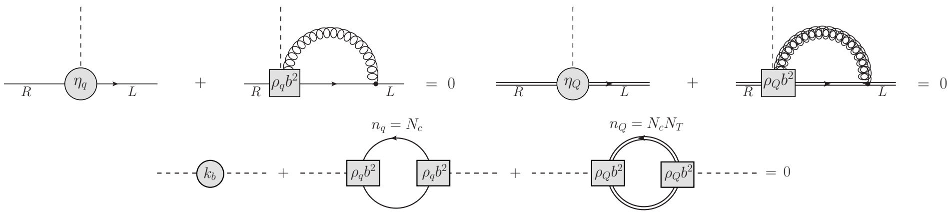

Figure 1: The lowest loop order cancellations of the Yukawa terms (top panel) and scalar kinetic operator (bottom panel) implied in the Wigner phase by the tuning conditions determining $\eta_{q\,cr}$, $\eta_{Q\,cr}$ and $k_{b\,cr}$, respectively. Boxes represent the insertion of the quark and Tera-quark Wilson-like vertices, the disc the insertion of the scalar kinetic term. Double lines are Tera-particles.

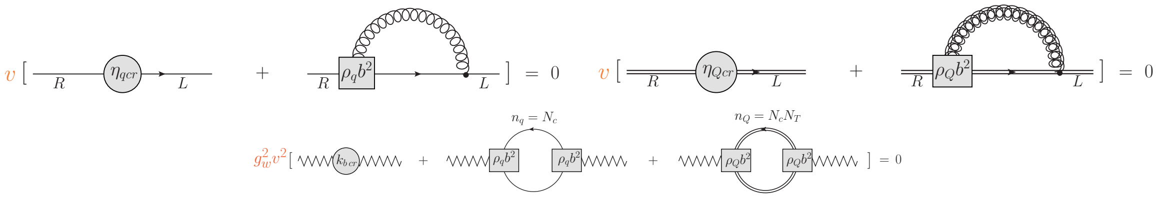

Figure 2: The mechanism underlying the cancellation of the Higgs-like mass of quark and Tera-quark (top panel) and W (bottom panel) occurring in the NG phase of the critical theory.

In the NG phase the tuning conditions entail the cancellation of the Higgs-like mass of quarks, Tera-quarks and W's, as schematically represented in fig. 2. Elementary particles will, however, get a NP-ly generated mass. Indeed, by extending to the present case the analysis (developed in [1]) of the formally O(b^2) operators necessary to describe in the Symanzik expansion the NP effects related to the spontaneous breaking of the (recovered) $\tilde{\chi}_L \times \tilde{\chi}_R$ symmetry, one identifies the following set of operators [10]

$$O^s_{6,\bar{Q}Q} = b^2\alpha_s\,\rho_Q\Lambda_T|\Phi|\Big[\bar{Q}_L \mathcal{D}^{AGW} Q_L + \bar{Q}_R \mathcal{D}^{AG} Q_R\Big]\,, \tag{9}$$

$$O^T_{6,\bar{Q}Q} = b^2\alpha_T\,\rho_Q\Lambda_T|\Phi|\Big[\bar{Q}_L \mathcal{D}^{AGW} Q_L + \bar{Q}_R \mathcal{D}^{AG} Q_R\Big]\,, \tag{10}$$

$$O_{6,AA} = b^2\alpha_s\,\rho_Q\Lambda_T|\Phi|F^A\cdot F^A\,,\;\; O_{6,GG} = b^2\alpha_T\,\rho_Q\Lambda_T|\Phi|F^G\cdot F^G\,,\;\; O_{6,WW} = b^2\alpha_w\,\rho_Q\Lambda_T|\Phi|F^W\cdot F^W \tag{11}$$

NP masses emerge from the kind of self-energy diagrams shown in fig. 3 in which the operators (9)–(11) are combined with appropriate Wilson-like terms. These diagrams are finite owing to the exact UV-IR compensation and all of $O(\Lambda_T)$ times gauge coupling dependent coefficients.

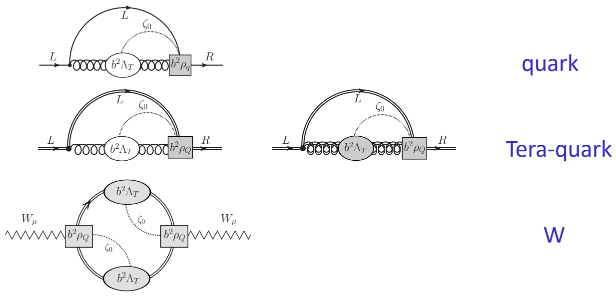

Figure 3: Self-energy diagrams giving NP masses to quarks, Tera-quarks and W. Blobs represent insertions of the NP Symanzik operators $O_{6,AA}$ (quark and Tera-quark), $O_{6,GG}$ (Tera-quark) and $O^T_{6,\bar{Q}Q}$ (W).

2.1 The critical QEL in the NG phase

Following the same line of arguments used in ref. [1], one gets for the $d = 4$ piece of the QEL of the critical theory in the NG phase the expression

$$\Gamma^{NG}_{4\,cr}(q, Q; \Phi; A, G, W) = \frac{1}{4}\Big(F^A \cdot F^A + F^G \cdot F^G + F^W \cdot F^W\Big) + \tag{12}$$
$$+\Big[\bar{q}_L \,\mathcal{D}\!\!\!/^{\,WA} q_L + \bar{q}_R \,\mathcal{D}\!\!\!/^{\,A} q_R\Big] + C_q\Lambda_T \left(\bar{q}_L U q_R + \bar{q}_R U^\dagger q_L\right) +$$
$$+\Big[\bar{Q}_L \,\mathcal{D}\!\!\!/^{\,WAG} Q_L + \bar{Q}_R \,\mathcal{D}\!\!\!/^{\,AG} Q_R\Big] + C_Q\Lambda_T \left(\bar{Q}_L U Q_R + \bar{Q}_R U^\dagger Q_L\right) + \frac{1}{2}c_w^2\Lambda_T^2 \mathrm{Tr}\,[(\mathcal{D}^W_\mu U)^\dagger \mathcal{D}^W_\mu U]\,.$$

From a detailed analysis of the diagrams in fig. 3 (see ref. [10]) one can read-off the parametric dependence of the mass of quarks, Tera-quarks and W's at the leading loop order. One finds

$$m_q^{NP} = C_q\,\Lambda_T\,, \quad C_q = O(\alpha_s^2)\,, \qquad m_Q^{NP} = C_Q\,\Lambda_T\,, \quad C_Q = O(\alpha_T^2, \ldots) \tag{13}$$
$$M_W^{NP} = C_w\,\Lambda_T\,, \quad C_w = \sqrt{\alpha_w}\,c_w\,, \quad c_w = k_w O(\alpha_T, \ldots)\,. \tag{14}$$

Masses are not affected by power divergencies thanks to the $\chi_L \times \chi_R$ symmetry. They are "naturally small", owing to the enhanced (chiral) symmetry of the massless theory, in line with the 't Hooft notion of naturalness [4].

We end the section by observing that, as remarked in the Introduction, one can prove that, upon integrating out the (heavy) Tera-dof's in the critical model (3), the resulting LEEL, which incorporates the "light" (on the Λ_T scale) 125 GeV (W^+W^-/ZZ bound) state detected at LHC, displays new terms with respect to those in eq. (12) making it to closely resemble the SM Lagrangian. We do not reproduce here the proof of this statement. It can be found in ref. [10] (see also [13]).

3. Universality

A key point that needs to be thoroughly discussed is to what extent the NP mass predictions we have derived above are "universal", or in other words to what extent their value depends on the exact form of the $d > 4$ Wilson-like terms that one decides to introduce in the fundamental Lagrangian. Actually it turns out that the power of the gauge coupling multiplying the RGI in the formula expressing the NP masses at the lowest loop order may depend on the dimensions of such chiral breaking terms. For instance, one can see that generically the higher is the dimension of the Wilson-like terms in the Lagrangian the larger will be the power of the gauge couplings in front of the RGI scale in the mass formulae. This state of affairs may appear to be a blunt violation of universality, however, one could imagine exploiting this dependence to try to interpret family mass hierarchy (from heavy to light) as due to Wilson-like terms of increasing dimensions.

As for the dependence of the NP masses upon the ρ parameters, one can prove [11] that in the case of a theory with only quarks and W's (and not Tera-quarks or leptons) their mass is actually ρ independent. If other fermions are present, be them Tera-particles and/or leptons, NP masses will be (mildly depending) functions of the ratios of the various ρ parameters.

4. Conclusions and Outlook

It was shown in [1] that, as an alternative to the Higgs mechanism, elementary fermion masses can be NP-ly generated in strongly interacting theories where chiral symmetry, broken at the UV cutoff level by irrelevant Wilson-like terms, is recovered at low energy owing to the tuning of certain Lagrangian parameters. This approach provides a neat solution of the Higgs mass tuning problem simply because there is no fundamental Higgs boson around.

To cope with the magnitude of the top (and W) mass, super-strongly interacting (Tera) particles, gauge invariantly coupled to standard matter, are conjectured to exist so as to have a theory with an RGI scale Λ_T of the order of a few TeV's. One can show [10] that the simplest model discussed in ref. [1] can be extended to incorporate weak interactions and the Tera-particles [2]. Upon integrating out the (heavy) Tera-dof's the resulting LEEL, valid at momenta$^2 \ll \Lambda_T^2$, is seen to closely resemble the SM Lagrangian [10] (see also [13]).

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[2] In a similar way one could introduce leptons and hypercharge interactions, an issue that will be discussed in ref. [11].