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STUDYING THE UNIFIED COMPOSITENESS IN e^+e^- COLLISIONS

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Abstract

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In the framework of the unified compositeness of leptons, quarks and Higgs bosons, the linearization of the minimal nonlinear standard model $G/H = SU(3)_L \times U(1)/SU(2)_L \times U(1)_Y$ via the hidden local symmetry $\hat{H}_{loc} = SU(2)_L \times U(1)_Y$ is briefly described. Additional hypothesis of vector boson dominance (VBD) of the SM gauge interactions is considered. Restrictions on the universal dominant residual fermion-fermion, fermion-boson and boson-boson interactions due to the VBD are investigated. Manifestations of the residual interactions at the 2 TeV e^+e^- linear collider are studied. It is shown that the common substructure could be investigated at the collider in the processes $e^+e^- \to \bar{f}f$ up to the compositeness scale $\mathcal{O}(50$ TeV) and in the processes $e^+e^- \to ZH$ and W^+W^- up to $\mathcal{O}(25$ TeV), which lies in the naturally preferred deca-TeV region for the unified compositeness.

Аннотация

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В рамках объединенной композитности лептонов, кварков и хиггсовских бозонов кратко описана линеаризация минимальной нелинейной стандартной модели $G/H = SU(3)_L \times U(1)/SU(2)_L \times U(1)_Y$ посредством скрытой локальной симметрии $\hat{H}_{loc} = SU(2)_L \times U(1)_Y$. Рассмотрена дополнительная гипотеза векторно-бозонной доминантности (ВБД) в калибровочных взаимодействиях стандартной модели. Получены ограничения на универсальные доминантные остаточные фермион-фермионные, фермион-мезонные и бозон-бозонные взаимодействия, возникающие вследствие ВБД. Изучены проявления этих универсальных взаимодействий на 2-ТэВ e^+e^--линейном коллайдере. Показано, что на таком коллайдере общая субструктура может быть исследована вплоть до масштаба составленности $\mathcal{O}(50$ ТэВ) в процессах $e^+e^- \to \bar{f}f$ и до $\mathcal{O}(25$ ТэВ) в процессах $e^+e^- \to ZH$ и W^+W^-, что лежит в предпочтимой из соображений натуральности декатэвной области объединенной композитности.

Introduction

The scheme of the unified compositeness of leptons, quarks and Higgs bosons, with their common substructure, furnishes one of the promising ways to go beyond the Standard Model (SM). Treating the SM Higgs doublet as the Goldstone boson in the scheme, one can solve, in particular, the naturalness problem of the Higgs sector in the SM without supersymmetry. A nonlinear model has been constructed in the lines described above by one of the present authors (Yu.F.P.) in refs. [1,2]. Here the SM is considered to be just a renormalizable part of the "low energy" effective field theory due to the unified compositeness.

The theory is based on some rather general assumptions about symmetry properties. Let the hypothetical hyperstrong interactions responsible for the internal binding of the SM composite particles possess a global chiral symmetry G. Under the hyperstrong confinement, the symmetry G breaks down to some its subgroup $H \subset G$ at the scale $\mathcal{F}$. In this, the true Goldstone bosons which are ultimately identified, in particular, as the Higgs doublet appears. The unbroken symmetry H must contain the SM symmetry $SU(2)_L \times U(1)_Y$. Thus, at the first stage, the electroweak symmetry remains unbroken. Ultimate taking into account the gauge quantum corrections, corresponding to some extended electroweak symmetry $I_{loc} \subset G$, results in the SM electroweak symmetry breaking at the Fermi scale $v \ll \mathcal{F}$. If this breaking happens only under two-loop corrections, the naturalness relation between the scales v and $\mathcal{F}$ takes place: $\mathcal{F} = \mathcal{O}(m_W/\alpha_W)$. So, $\mathcal{F}$ is expected to lie naturally in the deca-TeV region: $\mathcal{F} = \mathcal{O}(10 \text{ TeV})$. The minimal extension of the SM symmetry to implement such a scenario is given by the choice $G = SU(3)_L \times U(1)$ and $H = SU(2)_L \times U(1)_Y$, the intrinsic local subgroup being $I_{loc} = SU(2)_L \times U(1)_Y \times U(1)_{Y'}$. The corresponding nonlinear model G/H may be called the Minimal Nonlinear Standard Model (MNSM).

In what follows, we describe in short the linearization of the model via the phenomenon of the hidden local symmetry. Then we present the crucial phenomenological consequences of the unified compositeness scheme.

1. Universal Residual Interactions

As the nonlinear model, the MNSM is built on the nonlinear realization of G that becomes linear when restricted to H [3]. Such a model is equivalent, at least, at the classical level, to the model with linearly realized symmetry $G \times \hat{H}_{loc}$ [4]. Here $\hat{H}_{loc}$ is the hidden local symmetry with the appropriate auxiliary gauge bosons. In the context of the MNSM the phenomenon of the hidden local symmetry was studied in ref. [2]. The essence of the latter one is as follows.

In the linear model, the field variable is the element of the whole group G which can be parametrized as:

$$\hat{u} = uh, \;\; h \in H \tag{1}$$

and

$$u = e^{i\phi' Y'/\mathcal{F}'} e^{i(\phi_\alpha X^{\dagger\alpha} + h.c.)/\mathcal{F}} \in G/H. \tag{2}$$

Here ϕ is the Higgs-Goldstone doublet, ϕ' is the Goldstone boson corresponding to the broken hypercharge Y', with $\mathcal{F}$ and $\mathcal{F}'$ being the symmetry breaking mass scales. The following transformation law under $g \times \hat{h}(x) \in G \times \hat{H}_{loc}$ takes place:

$$g \times \hat{h}(x) : \;\; \hat{u} \to g \hat{u} \hat{h}^\dagger(x). \tag{3}$$

The linear model describes spontaneous/dynamical symmetry breaking $G \times \hat{H}_{loc} \to H$, with the total local symmetry being broken as $I_{loc} \times \hat{H}_{loc} \to H_{loc} = SU(2)_L \times U(1)_Y$.

To construct the Lagrangian of the linear model one has to introduce the modified differential 1-form $\hat{\omega}_\mu = 1/i \, \hat{u}^\dagger \hat{D}_\mu \hat{u}$, with $\hat{D}_\mu$ being the derivative covariant both under the intrinsic gauge symmetry I_{loc} and the hidden local symmetry $\hat{H}_{loc}$. Let's divide $\hat{\omega}_\mu$ into two parts: $\hat{\omega}_{\|\mu}$ which is parallel to G/H and $\hat{\omega}_{\perp\mu}$ orthogonal to it. Under $G \times \hat{H}_{loc}$ the parallel part $\hat{\omega}_{\|\mu}$ transforms homogeneously as in the original nonlinear model, and so does now orthogonal part $\hat{\omega}_{\perp\mu}$. It is precisely the introducing of the auxiliary vector fields $\hat{W}^i_\mu$ and $\hat{S}_\mu$, corresponding to $\hat{H}_{loc}$, that makes the transformation of $\hat{\omega}_\perp$ homogeneous. In the unitary under $\hat{H}_{loc}$ gauge, i.e. at $h \equiv 1$ in Eq. 1, the modified 1-form looks like

$$\begin{aligned} \hat{\omega}_{\|\mu} &= \omega_{\|\mu}, \\ \hat{\omega}^i_{\perp\mu} &= \omega^i_{\perp\mu} - \hat{g}\hat{W}^i_\mu, \\ \hat{\omega}^0_{\perp\mu} &= \omega^0_{\perp\mu} - \hat{g}_1\hat{S}_\mu, \end{aligned} \tag{4}$$

where ω_μ is the 1-form present in the original MNSM, $\hat{g}$ and $\hat{g}_1$ being some new strong coupling constants (expectedly, $\hat{g}^2/4\pi = \mathcal{O}(1)$).

In the Lagrangian of the linear model, the new terms appear. They are related with the orthogonal part of the modified 1-form. Here are some of the appropriate terms in the gauge sector:

$$\frac{\lambda \mathcal{F}^2}{2} (\hat{\omega}^i_{\perp\mu})^2 + \frac{\lambda_1 \mathcal{F}^2}{2} (\hat{\omega}^0_{\perp\mu})^2 + \cdots, \tag{5}$$

and for fermions they are

$$
\begin{aligned}
&\bar\psi\gamma_\mu i(\partial_\mu + i\hat g\hat W^i_\mu T^i + i\hat g_1\hat S_\mu Y)\psi \\
&+\kappa\bar\psi\gamma_\mu T^i\psi\hat\omega^i_{\perp\mu} + \kappa_1\bar\psi\gamma_\mu Y\psi\hat\omega^0_{\perp\mu} + \cdots .
\end{aligned} \tag{6}
$$

Here λ's and κ's are free parameters. It's to be noted that the matter fields ψ transform now only under $\hat H_{loc}$. The modified covariant derivative for them contains only the composite $\hat W_\mu$ and $\hat S_\mu$, but not the elementary W_μ and S_μ, the latter ones entering only through the nonminimal interactions.

Introducing the vector fields in such a way without kinetic terms is just a formal procedure. But we believe that the required kinetic terms are developed by the quantum effects, and the new composite vector bosons become physical. This takes place, e.g., in 2- and 3-dimensional nonlinear σ-models [5], as well as in the hadron physics as an accomplished fact.

From the Lagrangian of the linear model, one can read off the Lagrangian terms of the vector boson-current interactions:

$$
\mathcal{L}_{int} = -gW^i_\mu\Big((1-\lambda)J^i_\mu(\phi) + \kappa J^i_\mu(\psi)\Big) - \hat g\hat W^i_\mu\Big(\lambda J^i_\mu(\phi) + (1-\kappa)J^i_\mu(\psi)\Big). \tag{7}
$$

Here $J^i_\mu(\psi) = \bar\psi\gamma_\mu T^i\psi$ and $J^i_\mu(\phi) = \phi^\dagger i\tau^i/2 \overleftrightarrow{D}_\mu \phi$ are the usual SM isotriplet currents, with D_μ being the SM covariant derivative. To these isospin terms, one has to add the similar hypercharge isosinglet terms. Impose now the natural requirement that all the composite particles ϕ and ψ interact directly only with the composite vector bosons $\hat W$ and $\hat S$, but not with the elementary ones W and S. In other words, this is the well-known hypothesis of the vector boson dominance (VBD). This requirement allows one to fix the free parameters: $\lambda = 1$, $\kappa = 0$ and similarly for the isosinglet parameters.

The terms $(\hat\omega^i_\perp)^2$ and $(\hat\omega^0_\perp)^2$ describe the mass mixing of the elementary and composite gauge bosons, namely, W with $\hat W$ and S with $\hat S$. Diagonalizing these terms one gets two sets of physical vector bosons: the massless isotriplet and isosinglet physical bosons $\bar W^i$ and $\bar S$, as well as the massive ones $\bar{\hat W}^i$ and $\bar{\hat S}$ with masses of order $\mathcal{F}$. Due to the heavy physical vector boson exchange, the new low energy effective current-current interactions appear in addition to that of the SM:

$$
\begin{aligned}
\mathcal{L}^{(VBD)}_{int} &= -\frac{1}{2\mathcal{F}^2}\Big(J^i_\mu(\psi)J^i_\mu(\psi) + \eta_1 J^0_\mu(\psi)J^0_\mu(\psi)\Big) \\
&\quad -\frac{1}{\mathcal{F}^2}\Big(J^i_\mu(\psi)J^i_\mu(\phi) + \eta_1 J^0_\mu(\psi)J^0_\mu(\phi)\Big).
\end{aligned} \tag{8}
$$

Here η_1 is a free parameter, related to the original MNSM. Note that the VBD does not affect the low energy Higgs boson self-interactions, the latter ones being determined by the original MNSM alone:

$$
\mathcal{L}_{int}(\phi) = -\frac{1}{\mathcal{F}^2}\Big(\frac{1}{3}J^i_\mu(\phi)J^i_\mu(\phi) + J^0_\mu(\phi)J^0_\mu(\phi)\Big). \tag{9}
$$

All these expressions are valid only at energies $\sqrt{s} \ll \mathcal{F}$.

To resume, the unified compositeness plus the VBD prescribe the two-parameter set of the universal residual fermion-fermion, fermion-boson and boson-boson interactions, with their space-time and internal structure being fixed, the sign including. The unified compositeness scale $\mathcal{F}$ is expected to be in the deca-TeV region. Hence, the TeV energies are required to probe these new contact interactions.

2. Manifestations of Unified Compositeness

VBD of Electroweak Interactions. We have investigated a possibility to test the hypothesis of the VBD of electroweak interaction at the future 2 TeV e^+e^- linear collider via $e^+e^- \to \bar{f}f$ [6] and $e^+e^- \to ZH$, W^+W^- [7]. We chose for studying a set of integral characteristics: the relative deviation Δ in the total cross-sections from the SM values, the forward-backward charge asymmetry A_{FB}, the left-right polarization asymmetry A_{LR} and the mixed asymmetry A_{LR}^{FB}.

We have calculated these observables for the processes $e^+e^- \to \mu^+\mu^-$ $(\tau^+\tau^-)$, $\bar{b}b$, $\bar{c}c$, *jet jet* and for the Bhabha scattering $e^+e^- \to e^+e^-$ as the functions of the parameter η_1 for the various values of $\mathcal{F}$. The general results of these calculations are as follows. For all the processes (except the Bhabha scattering) all the asymmetries have the similar behaviour. First of all, there exists a particular value of $\eta_1 = \tan^2\theta_W \simeq 0.3$ when all the asymmetries coincide with those of the SM. The only way to unravel the contact interactions in this particular case is to study directly the total cross-sections. Another particular value of $\eta_1 = g_1^2\mathcal{F}^2/s$ provides the best case for studying the contact interactions, when all the asymmetries in all the processes saturate their maximal values.

To evaluate the statistical significance of the observed deviations we have considered the total cross-sections. Fig. 1 presents the reach for the scale $\mathcal{F}$ at 2σ level (95% C.L.) via the total cross-sections in the various $\bar{f}f$ channels. To this end, we took into account only the statistical errors and accepted the integrated luminocity $\int \mathcal{L}\, dt$ moderately to be 20 fb^{-1}. In the case of the Bhabha scattering $e^+e^- \to e^+e^-$ an optimal value of the cut-off, equal to 0.85, was chosen. Here the sensitivity is maximal due to the maximal suppression of the t-channel peak at the statistics still high enough. It is seen that in the processes $e^+e^- \to \bar{f}f$ the VBD can be tested for the unified substructure scale $\mathcal{F}$ up to $\mathcal{O}(50$ TeV$)$.

For the processes $e^+e^- \to ZH$ and W^+W^-, it proved to be of importance to consider the polarized cross-sections $\sigma(P_e)$, with P_e denoting the polarization of electron beam (the positron beam was taken to be unpolarized). So, we have studied the relative deviation $\Delta(P_e)$ in the polarized cross-section from that of the SM. In the cases of both ZH and WW pair production one has $|\Delta(-1)| \ll |\Delta(+1)|$. Hence one is lead to conclude that it is preferable to operate with the maximum right-handedly polarized electrons to observe as large deviations in the total cross-sections from the SM values as possible. The advantage of the right-handed polarization can be seen, e.g., from the picture that presents the scale $\mathcal{F}$ versus the parameter η_1, attainable at 95% C.L. (Fig. 2).

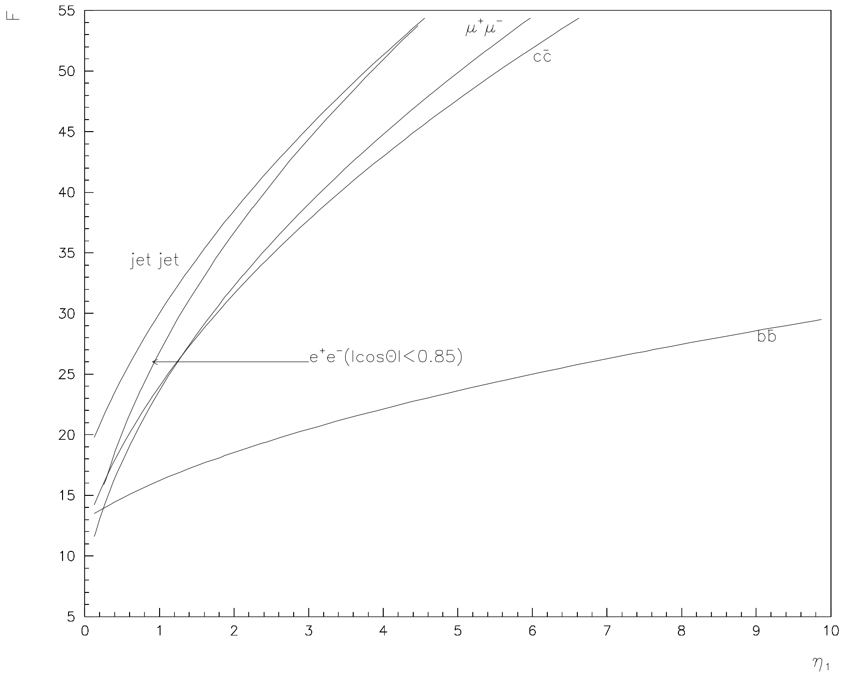

Fig. 1. The reach at 95% C.L. for the compositeness scale $\mathcal{F}$, vs. the parameter η_1, via studying the total cross-sections of the processes $e^+e^- \to \bar{f}f$.

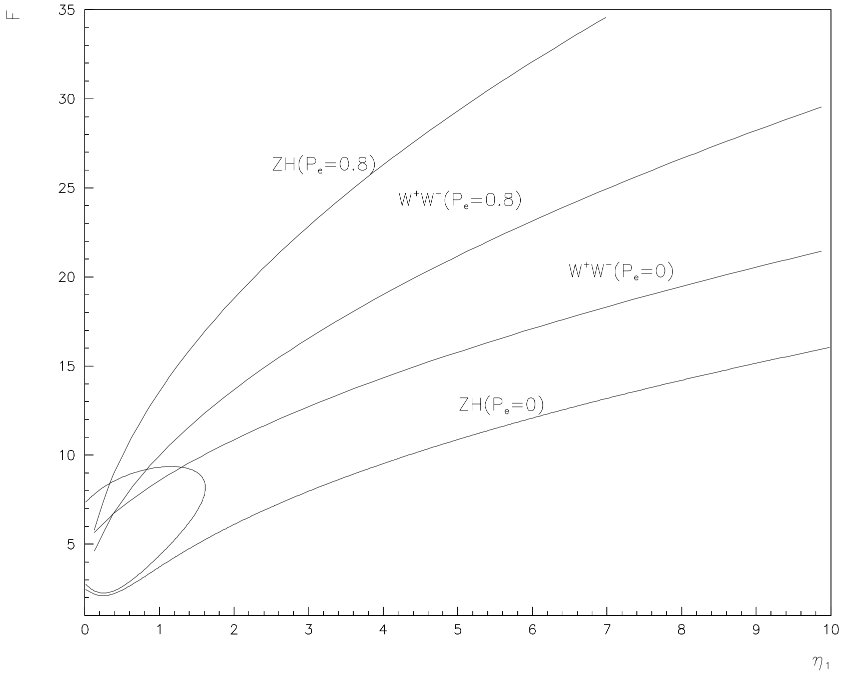

Fig. 2. The same as in Fig. 1 for the processes $e^+e^- \to ZH, W^+W^-$ with the various electron polarizations P_e ($m_H = 200$ GeV).

Thus, using the right-handed polarized electron beam the VBD can be tested up to the scale $\mathcal{F}$ of the order of 25 TeV in the e^+e^- annihilation into boson pairs. Here the calculations for the W^+W^- pair production have been made under the instrumental cut-off $|\cos\theta| \leq 0.8$. In addition, an optimal cut-off in the forward direction, whose sense is similar to that in the forward Bhabha scattering, has been found to be $\cos\theta \leq 0.3$.

Anomalous Triple Gauge Interactions. In addition to the VBD interactions, a lot of other "low energy" residual interactions is allowed in the scheme of the unified compositeness. In particular, the exotic triple gauge interactions (TGI) [8] are conceivable too, and can contribute to the W^+W^- pair production. The question arises as to what extent the two types of new interactions could imitate each other.

The anomalous TGI should originate from a kind of the SM extension. Here, the SM symmetry $SU(2)_L \times U(1)_Y$ could be realized either linearly or nonlinearly. In the case of the nonlinear realization (being still linear on the $U(1)_{em}$ subgroup), the nonlinearity scale Λ is just the SM v.e.v. v. Thus, this kind of extension has nothing to do with the unified compositeness we consider. On the other hand, for the linear SM symmetry realization the scale Λ is not directly related with v and could be as high as desired. Thus, we chose it to be the unified compositeness scale $\mathcal{F} = \mathcal{O}(10 \text{ TeV})$.

All the conceivable linearly realized residual interactions are described by the $SU(2)_L \times U(1)_Y$ invariant operators built of the SM fields [9,10]. All the operators which are relevant to the anomalous TGI vertices are naturally expected to be $\mathcal{O}(g)$ or less in the gauge couplings, but there is one exception $\mathcal{O}_{WS}$. The latter stems from the nonlinear generalization of the field strengths in the NMSM. The similar gauge kinetic terms of the isotriplet W and isosinglet S bosons have no gauge couplings. So, the same must naturally happen for $\mathcal{O}_{WS}$, for its origin is of the same nature.

Thus, we have retained the $\mathcal{O}_{WS}$ operator alone and have chosen the proper effective Lagrangian to be

$$\mathcal{L}_{eff} = \frac{C}{2}\frac{1}{\mathcal{F}^2}\mathcal{O}_{WS} \equiv \frac{C}{2}\frac{1}{\mathcal{F}^2}\phi^\dagger\frac{\tau_i}{2}\phi W^i_{\mu\nu}S_{\mu\nu}, \tag{10}$$

where $C = \mathcal{O}(1)$. With account for all the contributions from this operator we have found that the deviations from the SM predictions even in the most enhanced TGI case are much smaller than those in the VBD case. So, the VBD is, in fact, dominant.

Conclusions

The main results of our study are as follows:

- VBD of the SM gauge interactions is expected to be the universal dominant low energy feature of the unified compositeness of leptons, quarks and Higgs bosons.
- VBD of the SM electroweak interactions can be tested at the 2 TeV e^+e^- linear collider for the unified compositeness scale $\mathcal{F}$ up to $\mathcal{O}(50 \text{ TeV})$ in $e^+e^- \to \bar{f}f$ and up to $\mathcal{O}(25 \text{ TeV})$ in $e^+e^- \to ZH$, W^+W^-.
- Processes $e^+e^- \to \bar{f}f$ with various final fermions and $e^+e^- \to ZH$, W^+W^- are mutually complimentary. I.e., at any values of compositeness scale $\mathcal{F}$ and parameter

η_1 (but for $\eta_1 \simeq 0.3$) one can choose the environments where the deviations from the SM are not zero. More than that, these deviations are tightly correlated.

- For $e^+e^- \to ZH$, W^+W^- it is of importance to operate with the right-handed electrons to observe as large deviations in the total cross-sections as possible.
- For $e^+e^- \to e^+e^-$ and W^+W^- there exist the optimal angular cuts-off $|\cos\theta| \leq 0.85$ and $-0.8 \leq \cos\theta \leq 0.3$, respectively, at which the attainable compositeness scale $\mathcal{F}$ is maximal.

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