Signatures of lower scale gauge coupling unification in the Standard Model due to extended Higgs sector

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The gauge coupling unification can be achieved at a unification scale around $5 \times 10^{13}$ GeV if the Standard Model scalar sector is extended with extra Higgs-like doublets. The relevant new scalar degrees of freedom in the form of chiral $Z^*$ and $W^*$ vector bosons might “be visible” already at about 700 GeV. Their eventual preferred coupling to the heavy quarks explains the non observation of these bosons in the first LHC run and provides promising expectation for the second LHC run.

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INTRODUCTION

At present the Standard Model (SM) successfully describes all experimental data in particle physics. Moreover, it is theoretically consistent and applicable up to the Plank scale, $M_P \approx 1.2 \times 10^{19}$ GeV. On the other hand, there are many natural questions, which cannot be answered within the SM framework. For example, chiral anomalies are canceled only when quarks and leptons are considered simultaneously. At the same time these two sectors are completely independent within the SM.

The hope that the different gauge coupling constants of the SU(3)$_C \times$SU(2)$_W \times$U(1)$_Y$ SM group meet at a single unification point has failed [1]. Therefore, if we, nevertheless, expect such unification, new physics should be introduced at some scale above the electroweak unification. In this paper we will consider the one-loop approximation to the gauge coupling evolution modifying only the Higgs sector of the SM.

The matter sector of the SM consists of electroweak doublets: fermionic and bosonic ones. The SM contains only one bosonic doublet of the Higgs fields. We will assume that the number of the bosonic doublets $N$ above some scale could be greater than one, while the number of the fermionic doublets is not modified. At present there are practically no limitations on the number $N$ of the Higgs doublets from the precision low-energy measurements [2].

The evolution of the gauge coupling constants in the one-loop approximation reads

$$\alpha_i^{-1}(\mu) = \alpha_i^{-1}(\mu_0) - \frac{b_i}{2\pi} \ln \frac{\mu}{\mu_0},$$

where the constants $b_i$ are given by the known formulas

$$b_1 = 4 + \frac{N}{10},$$

$$b_2 = -2 \frac{11}{3} + 4 + \frac{N}{6},$$

$$b_3 = -3 \frac{11}{3} + 4.$$ (2)

We will start the evolution of $\alpha_i^{-1}$ at the initial point \[\mu_0 = M_Z = 91.1876 \pm 0.0021 \text{ GeV}\] using the most precise physical constants [3],

$$\hat{\alpha}(M_Z) = 1/127.940 \pm 0.014,$$

$$\sin^2 \theta(M_Z) = 0.23126 \pm 0.00005,$$

$$\alpha_s(M_Z) = 0.1185 \pm 0.0006.$$ (3)

Then the initial corresponding gauge coupling constants can be expressed as

$$\alpha_1^{-1}(M_Z) = \frac{3 \cos^2 \theta(M_Z)}{5} \hat{\alpha}(M_Z) = 59.012 \pm 0.014,$$

$$\alpha_2^{-1}(M_Z) = \frac{\sin^2 \theta(M_Z)}{\hat{\alpha}(M_Z)} = 29.587 \pm 0.007,$$ (4)

$$\alpha_3^{-1}(M_Z) = \alpha_s^{-1}(M_Z) = 8.439 \pm 0.043,$$

where the factor of $3/5$ in the definition of $\alpha_3$ is included for the proper normalization of the hypercharge generator of the U(1)$_Y$ group.

For one SM Higgs doublet, $N = 1$, there is no unique scale $\hat{\mu}$, where $\alpha_1^{-1}(\hat{\mu}) = \alpha_2^{-1}(\hat{\mu}) = \alpha_3^{-1}(\hat{\mu})$. However, if at some scale $\hat{\mu}$ new states start to make additional contribution to the gauge coupling evolution, this unification point can be found. Since the evolution of the gauge coupling constants obeys linear behavior with $\ln \mu$, simple formulas can be obtained

$$\hat{\mu} = M_Z \exp \left[ -\frac{2\pi \epsilon_{ijk}(b_i - b_j)\alpha_k^{-1}(M_Z)}{\epsilon_{ijk}(b_i - b_j)\Delta b_k} \right],$$

$$\bar{\mu} = M_Z \exp \left[ -\frac{2\pi \epsilon_{ijk}(\Delta b_i - \Delta b_j)\alpha_k^{-1}(M_Z)}{\epsilon_{ijk}(b_i^0 - b_j^0)\Delta b_k} \right],$$

$$\alpha^{-1}(\hat{\mu}) = \frac{\epsilon_{ijk} \Delta b_i b_j^0 \alpha_k^{-1}(M_Z)}{\sum_k \epsilon_{ijk} \Delta b_k b_j^0},$$

where $\Delta b_i = b_i - b_i^0$ are the differences between the constants $b_i$ from eq. (2) and their SM values $b_i^0$ at $N = 1$.

Since the differences $\Delta b_i$ are proportional to $N - 1$ or zero, it is obvious from eq. (3) that the unification scale...
\[ \hat{\mu} = M_Z \exp \left[ \frac{5\alpha^{-1}_1(M_Z) - 3\alpha^{-1}_2(M_Z) - 2\alpha^{-1}_3(M_Z)}{22} \right] \]

\[ = 5.09^{+0.09}_{-0.08} \times 10^{13} \text{ GeV}, \]

\[ \alpha^{-1}(\hat{\mu}) = \frac{35\alpha^{-1}_1(M_Z) - 21\alpha^{-1}_2(M_Z) + 30\alpha^{-1}_3(M_Z)}{44} \]

\[ = 38.57 \pm 0.03, \quad (6) \]

Although the solution, eq. (5), always exists, the physically acceptable result \( \hat{\mu} > M_Z \) is possible only for \( N \geq 8 \). Therefore, the lightest states, which can provide unification, correspond to \( N = 8 \) and the scale

\[ \hat{\mu} = 692^{+144}_{-120} \text{ GeV}. \quad (7) \]

In the following only this possibility will be discussed.

**WEAK-DOUBLET SPIN-1 BOSONS**

Although the unification of the gauge coupling constants is reached (Fig. 1), the extension of the SM with seven additional Higgs doublets looks awkward. Here we will propose a different interpretation of the given result.

Their interactions with SU(2)_W \times U(1)_Y gauge fields are similar to the interactions of the SM Higgs doublet due to identical internal quantum numbers. The massive vector boson has three physical degrees of freedom and contributes to the gauge coupling evolution in the one-loop approximation three times more strongly than the scalar boson. Therefore, introduction of one pair of scalar and vector doublets is equivalent to the four Higgs doublets content.

So, the solution with \( N = 8 \) can be interpreted as an extension of the SM Higgs sector with one additional Higgs doublet and two corresponding vector doublets. That is exactly the set of fields which was proposed in [5]. It was shown [8] that the second pair of scalar and vector doublets with opposite hypercharges is necessary to cancel the chiral anomaly.

Due to their quantum numbers, in the leading order the vector doublets can only have anomalous (magnetic moment type) interactions with the SM fermions,

\[ \frac{1}{M} D_\mu V^c \left( g^d_{LR} Q_L \sigma^{\mu\nu} \bar{d}_R + g^e_{LR} L \sigma^{\mu\nu} e_R \right) \quad (8) \]

\[ + \frac{g^u_{LR}}{M} D_\mu V^c Q_L \sigma^{\mu\nu} u_R + \text{h.c.,} \quad (9) \]

where \( V^c \equiv (-W^{++}, Z^\mu) \) is the charge-conjugated doublet; \( Q_L \equiv (u_L, d_L) \) and \( L \equiv (e_L, \nu_L) \) are the left-handed quark and lepton doublets respectively. \( D_\mu \) are the usual SU(2)_W \times U(1)_Y covariant derivatives, and the obvious group and family indices are suppressed. \( M \) is the scale of new physics and \( g^u,d,e_{LR} \) are dimensionless constants.

The derivative couplings lead to previously unexplored angular distributions [9] and to unique signatures for detection of these bosons at the hadron colliders. Our project for their search was accepted by the ATLAS Collaboration and the corresponding analysis of the experimental data was performed. In the simplest reference model [10] used in the analysis, the dimensionless constants were fixed to be proportional to the electroweak gauge coupling and the family universality was assumed. The scale of new physics was chosen to be equal to the mass of the new bosons. The final Run-I ATLAS results [6] put the following 95% CL limits on new boson masses:

\[ M_{W^\ast} > 3.21 \text{ TeV}, \quad M_{Z^\ast} > 2.85 \text{ TeV}. \quad (10) \]

At first glance, these results exclude the possibility of existence of the lightest states with masses \( M \sim \hat{\mu} \approx 700 \text{ GeV} \) (see eq. (7)). However, they were derived from analyzing the final states with light leptons (electrons, muons and missing neutrinos) as the clearest channels for new heavy resonance search at hadron colliders. It was also assumed that the heavy resonance had to be produced in direct fusion of the lightest quark-antiquark pairs from the colliding protons. In other words, the quark-lepton and family universality was assumed.

However, the assumption of the family universality is natural for the vector fields from the adjoint repre-
sentations of the gauge group in order to avoid tree-level flavor-changing neutral currents, whereas the scalar Higgs doublet from the fundamental representation interacts mainly with the fermions from the third family, which is the source of the flavor violation in Nature. Since the vector doublets come along with the scalar doublets, it is more natural to suggest a similar pattern of couplings for the vector doublets too.

The presence of two Higgs doublets can also be a source of tree-level flavor-changing neutral currents. In order to prevent that, we assume that one doublet pair couples only to up-type quarks, while the other couples to down-type quarks and charged leptons only [10]. Since the coupling strengths are proportional to the mass of the fermions, in this simple model the $W^*$ and $Z^*$ bosons from the vector doublet couple mainly to the right-handed $t$-quark singlet (see eq. 9)

$$\frac{g}{M_W^*} \left( \partial_\mu W_{\nu R}^* \sigma^{\mu\nu} b_L + \partial_\mu W_{\nu R}^* \partial_\rho \sigma^{\rho\nu} b_L \right)$$

(11)

$$+ \frac{g}{\sqrt{2} M_Z^*} \left( \partial_\mu \text{Re} Z_{\nu R}^* \gamma^\mu t + i \partial_\mu \text{Im} Z_{\nu R}^* \gamma^\mu \gamma^5 t \right),$$

(12)

where $\text{Re} Z^*$ and $\text{Im} Z^*$ are the properly normalized CP-even and CP-odd neutral states.

**EXPERIMENTAL SIGNATURES**

Theoretical and experimental aspects for extra scalar bosons search from two-Higgs-doublet models are already extensively studied [11]. Therefore, we concentrate here on a less-known issue connected with the production and decay of vector doublets.

Interactions of vector doublets resemble scalar Higgs doublet couplings. Therefore, experimental signatures should be within the scope of those for the Higgs searches, although with obvious differences due to different spins.

For example, the leading channel for the Higgs production at the LHC, gluon-gluon fusion through the $t$-quark loop, is not operative or suppressed for production of vector bosons due to the Landau–Yang theorem [12]. Vector fields cannot have nonzero vacuum expectation value unless Lorentz symmetry violation exists. Therefore, analogs of the Higgs-strahlung and weak vector boson fusion production processes are also absent for the vector doublet boson production. For the same reason the new vector boson cannot decay into two photons or two $Z$ bosons, which are used as very clean channels for precise reconstruction of the Higgs mass. The only highly suppressed processes of heavy quark–antiquark fusion can produce resonantly the new vector bosons (Fig. 2).

The final signature of the first process (the upper left panel of Fig. 2) $gg \to ttZ^* \to tt\ell\ell$ is already in the sights of the standard model group [13] and the exotic group [14]. Although the SM Higgs boson mass is below the threshold for the $tt$-quarks production, the process for the associated Higgs production with a top-quark pair in multi-lepton final states [15] can mimic the signature of the first process.

Since the SM cross section $\sigma_{tt\ell\ell}^{\text{SM}} \approx 1 \text{ fb}$ at $\sqrt{s} = 8 \text{ TeV}$ is very small [16] we can put upper limit on the coupling constant of the neutral vector bosons from eq. (12) $g^* < 2$ assuming $M_{Z^*} \approx 700 \text{ GeV}$ from the direct 95% CL constraint $\sigma_{tt\ell\ell}^{\text{exp}} < 32 \text{ fb}$ [13]. From here on the CalcHEP package [17] is used for all numerical estimations.

The final signature of the second process (the upper right panel of Fig. 2) $gg \to gbW^* \to gbX$ coincides with the associated production of the Higgs boson with a top-quark pair and its decay into bottom quarks, although with absolutely different kinematics. Both collaborations have already searched for this final state [18].

The third process for the $W^*$ production (the bottom panel of Fig. 2) $gg \to ttW^* \to tt\ell\ell$ has a cross section comparable with the second process and leads to a yet unexplored final signature. This signature is much simpler than the previous ones and can be used even for direct reconstruction of the $b\bar{b}$-invariant mass.

As far as it is impossible to disentangle jets produced by quarks or antiquarks, we will use both possibilities, $tb$ and $b\bar{t}$, in order to construct the invariant mass, $m_{tb}$.

The nonresonant $tb$ contribution (dark red color) is also distributed over the whole region of possible invariant masses and is negligible under the peak from the $b\bar{t}$ contribution (light cyan color).

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1 Only recently the CMS Collaboration has announced their analysis [19] using this final state for a charged Higgs boson search.
play the role of some of scalar degrees of freedom. In physics is reached at total number of 8 Higgs doublets, active, can be well below 1 TeV. However, this scale of new scale, at which new scalar degrees of freedom become ac- pend on the extra Higgs doublets, whereas a new physics other scales known in the literature and does not de- doublets. As a result, the unification scale is lower than the Standard Model scalar sector only with extra Higgs achieved in the one-loop approximation by extension of see-saw mechanism [20]. Here $v$ with precision low-energy data.

It is shown that the gauge coupling unification can be achieved in the one-loop approximation by extension of the Standard Model scalar sector only with extra Higgs doublets. As a result, the unification scale is lower than other scales known in the literature and does not de- pend on the extra Higgs doublets, whereas a new physics scale, at which new scalar degrees of freedom become ac- tive, can be well below 1 TeV. However, this scale of new physics is reached at total number of 8 Higgs doublets, which looks very awkward.

Therefore, we assume that spin-1 vector bosons can play the role of some of scalar degrees of freedom. In this case we get a compact fields content: two Higgs and two spin-1 doublets. However, such light states were not found in the first LHC run. The reason, as we see it, is in accepting the hypothesis of family universality of vector doublet interactions with quarks and leptons. If the vec- tor doublet interactions resemble the Higgs fermion couplings, the new spin-1 bosons cannot be produced in light quark–antiquark annihilation from the proton beams and cannot decay into light lepton pairs as well.

This means that the production and the decay of the new heavy bosons should be associated only with heavy $b$- and $t$-quarks. Moreover, the increasing gluon luminosity due to higher centre-of-mass energies in the second LHC run will lead to an order of magnitude higher cross sections for the considered processes than in the first LHC run. In conclusion, we would like to stress out that the new channel $gb \rightarrow tW^{*} \rightarrow t\bar{b}$ can be very useful for early new physics search.

**DISCUSSIONS**

In this paper we have shown that the extension of the SM Higgs sector leads to a unification scale around $5 \times 10^{13}$ GeV. This value has many specific features.

For example, if the Majorana mass of a sterile right-handed neutrino is of the order of the unification scale, then the light neutrino states should have the mass of the expected order $m_\nu \sim v^2/2\tilde{\mu} \approx 0.6$ eV due to the see-saw mechanism [20]. Here $v$ is the vacuum expectation value of the Higgs field. This not so high unification scale is closer to the allowed heavy Majorana neutrino masses for successful baryogenesis through leptogenesis [21]. This scale does not destroy naturality from the Planck scale $\delta m_{tb} \sim \tilde{\mu}^3/(4\pi^3)M_{Pl}^2 \approx 0.5$ GeV.

On the other hand, the new lightest states at the scale $\tilde{\mu} \approx 700$ GeV maintain naturality, solving the hierarchy problem [4]. The introduction of the spin-1 doublets with the vector degrees of freedom replaces the introduction of many scalar states with degenerate masses. According to [2], it is an important feature to avoid contradiction with precision low-energy data.

**CONCLUSIONS**

It is shown that the gauge coupling unification can be achieved in the one-loop approximation by extension of the Standard Model scalar sector only with extra Higgs doublets. As a result, the unification scale is lower than other scales known in the literature and does not de- pend on the extra Higgs doublets, whereas a new physics scale, at which new scalar degrees of freedom become ac- tive, can be well below 1 TeV. However, this scale of new physics is reached at total number of 8 Higgs doublets, which looks very awkward.

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