Bounds on scalar leptoquark and scalar gluon masses from current data on S, T, U

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Abstract

The contributions into radiative correction parameters S, T, U from scalar leptoquark and scalar gluon doublets are investigated in the minimal four color symmetry model. It is shown that the existence of the relatively light scalar leptoquarks and scalar gluons (with masses of order of 1 TeV or less) is consistent with the current experimental data on S, T, U and the more light particles (with masses below 400 GeV) improve the fit. In particular, the lightest scalar leptoquarks with masses below 300 GeV are consistent with the current data on S, T, U at $\chi^2 < 3.1(3.2)$ for $m_H = 115(300)$ GeV in comparison with $\chi^2 = 3.5(5.0)$ in the Standard Model. The lightest scalar gluon in this case is expected to lie below 850(720) GeV. The possible significance of such particles in the t-quark physics at LHC is emphasized and their effect on the gauge coupling constant unification is briefly discussed.

1 Introduction

By this talk I would like to call an attention to the possibility of scalar leptoquarks and scalar gluons relating to the four color quark-lepton symmetry to be relatively light.

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Apparently each of us is interested in a question what kind of the new physics beyond the Standard Model (SM) can exist at more high energies and how this new physics can manifest itself at the energies of the present and future colliders. One of the possible variants of such new physics can be the variant induced by the possible four color symmetry [1] between quarks and leptons. The immediate consequence of this symmetry is the prediction of the new gauge particles – vector leptoquarks with the masses of order of the mass scale M_c of the four-color symmetry breaking. In dependence on the model the lower limit on M_c can vary from $M_c \sim 10^{12}\ GeV$ [2] or $M_c \sim 10^5 - 10^6\ GeV$ [3] in GUT models with the four-color symmetry as an intermediate stage of symmetry breaking to $M_c \sim 1000\ TeV$ [4] or to $M_c \sim 100\ TeV$ or less in the models regarding the four-color symmetry as a primery symmetry [4–10]

It should be noted however that the four-color symmetry can manifest itself not only by the vector leptoquarks but also due to the new scalar particles such as scalar leptoquarks [11, 12] or scalar gluons [5, 6]. In particular, in addition to the vector leptoquarks the four color symmetry with the Higgs mechanism of splitting the masses of quarks and leptons (MQLS-model, [5,6]) predicts [13] the scalar leptoquarks and the scalar gluons of the doublet structure under the electroweak $SU_L(2)$-group. In this approach these doublets are responsible for splitting the masses of quarks from those of leptons and they are the partners of the standard Higgs doublet. What can we say about the masses of these scalar doublets?

These particles could manifest themselves through the radiative corrections. As is known if the new particles are relatively heavy ($m_{new} \gg m_Z$) their contributions into electroweak corrections can be approximately accounted by the formalism of the $S, T, U-$ parameters of Peskin and Takeuchi [14]. The current experimental data [15] give the next values of S, T, U which can be induced by a new physics

$$\begin{aligned} S_{new}^{exp} &= -0.03 \pm 0.11\ (-0.08), \\ T_{new}^{exp} &= -0.02 \pm 0.13\ (+0.09), \\ U_{new}^{exp} &= \quad 0.24 \pm 0.13\ (+0.01), \end{aligned} \tag{1}$$

where the central values assume $m_H = 115\ GeV$ and the change for $m_H = 300\ GeV$ is shown in parentheses. The S, T, $U-$ parameters are normalized so that in SM they are equal to zero ($S_{SM} = T_{SM} = U_{SM} = 0$).

In this talk I would like to discuss the bounds on the masses of the scalar

leptoquark and scalar gluon doublets wich are imposed by the current S, T, U data (1).

2 Brief description of the MQLS model

The MQLS-model to be used here is based on the $SU_V(4) \times SU_L(2) \times U_R(1)$-group and predicts the new gauge particles (vector leptoquarks $V\alpha\mu^{\pm}$ with electric charge $\pm 2/3$ and an extra neutral $Z'-$ boson) as well as the new scalar ones [5, 6].

The scalar sector of the model contains in general the four multiplets $\Phi_A^{(1)}$, $\Phi_a^{(2)}$, $\Phi_{i,a}^{(3)}$, $\Phi_i^{(4)}$, transforming according to the (4,1,1), (1,2,1), (15,2,1), (15,1,0) representations of the $SU_V(4) \times SU_L(2) \times U_R(1)$-group and having the vacuum expectation values η_1, η_2, η_3, η_4 respectively. Here $A = 1, 2, 3, 4$ and $i = 1, 2 ... 15$ are the $SU_V(4)$ indexes and $a = 1, 2$ is the $SU_L(2)$ one.

The scalar leptoquark and scalar gluon doublets $S_{a\alpha}^{(\pm)}$ and F_{ja} to be discussed here belong to the (15,2,1)-multiplet $\Phi_{i,a}^{(3)}$. This multiplet together with (1,2,1)-multiplet $\Phi_a^{(2)}$ generates the fermion masses by Higgs mechanism and splits the masses of quarks from those of leptons.

Below we consider the scalar leptoquark doublets in the case of the the simplest scalar leptoquark mixing and with neglect of the small parameter $\xi^2 = \frac{2}{3} g_4^2 \eta_3^2 / m_V^2 \ll 1$ of the model. In this case the scalar leptoquark doublets can be written as

$$S^{(+)} = \begin{pmatrix} S_1^{(+)} \\ c\ S_1 + s\ S_2 \end{pmatrix}, S^{(-)} = \begin{pmatrix} S_1^{(-)} \\ -s\ \overset{*}{S}_1 + c\ \overset{*}{S}_2 \end{pmatrix}, \tag{2}$$

where S_1, S_2 are the mass eigen states of the scalar leptoquarks with electric charge 2/3 and $c = \cos\theta$, $s = \sin\theta$, θ is the scalar leptoquark mixing angle.

The scalar gluon doublets in general case can be written as

$$F_j = \begin{pmatrix} F_{1j} \\ (\phi_{1j} + i\phi_{2j})/\sqrt{2} \end{pmatrix}, \tag{3}$$

where the charged fields F_{1j} and the neutral fields $\phi_{1j}, \phi_{2j}, j = 1, 2, ..., 8$ are the mass eigen state fields (in general case the real and imaginary parts ϕ_{1j}, ϕ_{2j} of the down component of the doublet F_j can be splitted in the mass).

The contributions $S^{(LQ)}$, $T^{(LQ)}$, $U^{(LQ)}$ and $S^{(F)}$, $T^{(F)}$, $U^{(F)}$ into S, T, U from the scalar leptoquark and scalar gluon doublets have been calculated

and analysed in ref. [16–18]. In the case of the scalar doublets of the forms (2), (3) the resulting contributions $S = S^{(LQ)} + S^{(F)}$, $T = T^{(LQ)} + T^{(F)}$, $U = U^{(LQ)} + U^{(F)}$ depend on seven masses and on the mixing angle θ. The contributions $T^{(LQ)}$ and $U^{(LQ)}$ from the scalar leptoquark doublets are not positive definite due to the $S_1 - S_2$- mixing and can be negative if $m_{S_1^{(+)}}, m_{S_1^{(-)}}$ are between m_{S_1} and m_{S_1} and the contributions $T^{(F)}$ and $U^{(F)}$ are also not positive definite and they are negative if m_{F_1} is between m_{ϕ_1} and m_{ϕ_2}.

The masses of the scalar leptoquark and scalar gluon doublets are generated by the Higgs mechanism of the symmetry breaking from the scalar potential $V(\Phi^{(SM)}, S^{(+)}), S^{(-)}, F)$ including the interactions of these doublets with the standard Higgs doublet. In this case we obtain some relations between the masses of scalar particles and the coupling constants of the scalar potential. As a result we have the new eight independent parameters of the model

$$m_{S_1^{(+)}}, m_{S_1^{(-)}}, m_{F_1}, \gamma_+, \gamma_-, \delta_S, \gamma_F, \delta_F, \tag{4}$$

where $\gamma_+, \gamma_-, \delta_S, \gamma_F, \delta_F$ are the coupling constants describing the interactions of the scalar leptoquark and scalar gluon doublets with the standard Higgs doublet.

For the stability of the vacuum the coupling constants in the scalar potential are supposed below to satisfy some conditions ensuring the positiveness of the scalar potential

$$V(\Phi^{(SM)}, S^{(+)}), S^{(-)}, F) > 0. \tag{5}$$

For validity of the perturbation theory the coupling constants in the scalar potential cannot be too large. We suppose below that all the coupling constants in the scalar potential do not exceed some maximal value λ_{max} ensuring the validity of perturbation theory. In the further numerical analysis we restrict ourselves by the values of λ_{max} from the region $\lambda_{max} = 1.0 - 4.0$ which give the reasonable values of the perturbation theory expansion parameter of order $\lambda_{max}/4\pi = 0.1 - 0.3$.

3 Fit of the model parameters and discussion

Varying the fitting parameters (4) we minimize χ^2 defined as

$$\chi^2 = \frac{(S - S^{exp}_{new})^2}{(\Delta S)^2} + \frac{(T - T^{exp}_{new})^2}{(\Delta T)^2} + \frac{(U - U^{exp}_{new})^2}{(\Delta U)^2},$$

where $\Delta S, \Delta T, \Delta U$ are the experimental errors in (1).

To clear up the possible effect of the scalar leptoquark and scalar gluon doublets on S, T, U we vary the masses of these particles so that

$$m_{S_1}, m_{S_2}, m_{S_1^{(\pm)}}, m_{F_1}, m_{\phi_1}, m_{\phi_2} \geq m_{scalar}^{lower}, \tag{6}$$

where m_{scalar}^{lower} is a lower limit on the masses of these particles. After minimization of χ^2 under condition (6) we have analysed the dependence of χ^2_{min} on this lower limit m_{scalar}^{lower} and on upper limit λ_{max} on the coupling constants of the scalar potential.

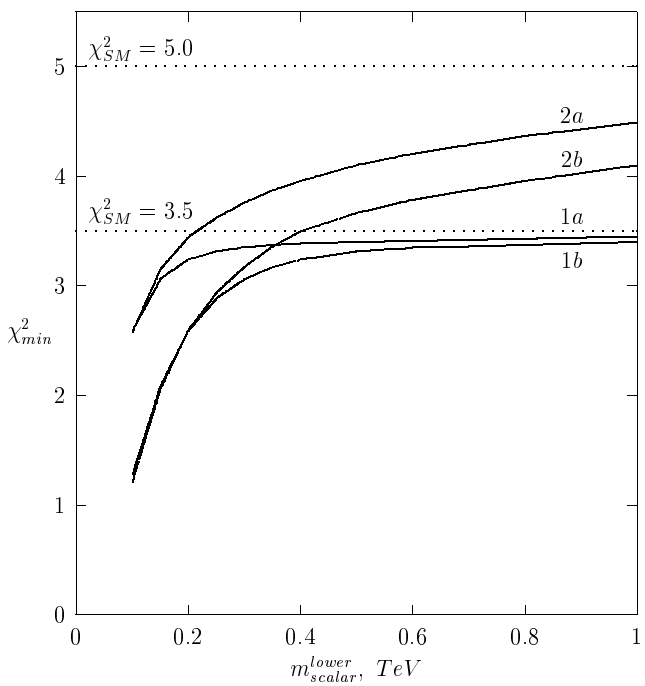

Figure 1: $\chi^2_{min}(m_{scalar}^{lower}, \lambda_{max})$ as a function of the lower limit m_{scalar}^{lower} on the masses of the scalar particles for $m_H = 115\ GeV$ (1) and for $m_H = 300\ GeV$ (2) at $\lambda_{max} = 1.0(a)$ and $\lambda_{max} = 4.0(b)$.

The Fig.1 shows $\chi^2_{min}(m_{scalar}^{lower}, \lambda_{max})$ as a function of the lower limit m_{scalar}^{lower} for $m_H = 115\ GeV$ (the curves 1) and for $m_H = 300\ GeV$ (the curves 2) at $\lambda_{max} = 1.0(4.0)$ (the curves $a(b)$) for the case without scalar leptoquark mixing ($\theta = 0$, this case is slightly preferred by χ^2 minimum). The horizontal lines denote $\chi^2_{SM} = 3.5$ and $\chi^2_{SM} = 5.0$ of the compatibility of the SM zero

values of S, T, U with the experimental data (1) at $m_H = 115\ GeV$ and $m_H = 300\ GeV$ respectively.

As seen from the Fig.1 the lower limit m_{scalar}^{lower} on the masses of the scalar leptoguarks and of the scalar gluons is allowed by data (1) to vary within wide limits from high values when the contributions from these particles into S, T, U are negligibly small to values of order of 1 TeV or less. It is interesting that in both cases the more light particles agree with the data (1) even slightly better than in the SM. For $m_H = 115\ GeV$ (the curves 1) such slight improvement of the agreement takes place for $m_{scalar}^{lower} < 400\ GeV$ whereas in the case of $m_H = 300\ GeV$ (the curves 2) such improvement is seen in all the region of the lightest masses of order of 1 TeV or less and it is more appreciable also for $m_{scalar}^{lower} < 400\ GeV$. This improvement at $m_{scalar}^{lower} < 400\ GeV$ takes place due to the mutual cancellation of the contributions into S and T from the scalar leptoquarks with those from the scalar gluons. In particular the scalar leptoquarks with the lightest masses of order of $m_{scalar}^{lower} < 300\ GeV$ (and for $\lambda_{max} = 4.0$) are compatible with the data (1) at $\chi^2 < 3.1(3.2)$ for $m_H = 115(300)\ GeV$ in comparison with $\chi^2_{SM} = 3.5(5.0)$ in the SM. The mass of the lightest scalar gluon in this case is expected to be $m_{\phi_2} < 850(720)\ GeV$.

The lightest scalar leptoquark masses of order $m_{scalar}^{lower} \lesssim 400\ GeV$ are compatible with the experimental limits resulting from the direct search for the leptoquarks. The most stringent of these limits are resulted from the pair production and for the scalar leptoquarks of the first generation they give [15]

$$m_{LQ} > 225\ GeV,\ \ 204\ GeV,\ \ 79\ GeV \tag{7}$$

under assuming the branching ratios $B(eq) = 1,\ 0.5,\ 0$ respectively. It should be noted that in the model under consideration the coupling constants of the scalar leptoquark doublets with the fermions (and those of the scalar gluon doublets) are proportional to the ratios of the fermion masses to the SM VEV $\eta = 246\ GeV$ ($g_f \sim m_f/\eta$, the general form of this interaction can be found in ref. [13]) and for ordinary quarks these coupling constants are small. The dominant decay modes of such leptoquarks are the modes with heavy quarks (predominantly with t-quark) whereas the branching ratio for the first generation is small $0 < B(eq) \ll 0.5$. So the lower experimental limit on the masses of such scalar leptoquarks can be near the lowest value in (7), the masses of the other scalar leptoquarks are in this case compatible

with other experimental limits (including those for the second and for the third generations) resulting from the direct search for leptoquarks.

It should be noted also that the light scalar leptoquarks can be also compatible with the indirect leptoquark mass limits resulting from the rare decays of $K_L^0 \to \mu e$ type. Due to the smallness of the coupling constants of the scalar leptoquark interaction with d- and s- quarks $g_d \sim m_d/\eta \sim 2 \cdot 10^{-5}$, $g_s \sim m_s/\eta \sim 0.5 \cdot 10^{-3}$ the contributions of the scalar leptoquarks into $K_L^0 \to \mu e$ width can be sufficiently small to satisfy the stringent experimental limit $Br(K_L^0 \to \mu e) < 4.7 \cdot 10^{-12}$ [15] on the branching ratio of this decay, even for the relatively light masses of the scalar leptoquarks.

Finally the data on $Z-$ physics seemingly do not exlude the relatively light scalar leptoquarks. In the case of one degenerate scalar leptoquark doublet these data give the lower limit on its mass of about $400\, GeV$ [19].

Thus, the current direct and indirect mass limits for leptoquarks do not exclude the relative light scalar leptoquark doublets considered here whereas the experimental data on S, T, U not only allow the existence of such particles but even slightly prefer them to have the masses of order of $m_{scalar}^{lower} < 400\ GeV$. Keeping in mind the sizable magnitude of the coupling constants of the scalar doublets with t-quark ($g_t \sim m_t/\eta \sim 0.7$, $g^2/4\pi \sim 0.04$) the search for such scalar leptoquarks and scalar gluons in the processes with t-quarks at LHC is of interest.

It should be noted that the presence of the so light new particles can also affect the new physics at high energies. In particular these particles can affect the gauge coupling constant unification in GUT approaches. The mass scale evolution of the running coupling constants $\alpha_i(\mu) = g_i^2/4\pi$, $i = 1, 2, 3$ of electromagnetic (under the appropriate normalization), weak and strong interactions can be described in one loop approximation by the equations

$$\alpha_i^{-1}(\mu) = \alpha_i^{-1}(m_Z) - (b_i/2\pi) ln(\mu/m_Z), \tag{8}$$

where $b_i = b_i^{(SM)} + \Delta b_i^{(new)}$ are the corresponding factors of the β-functions expansion. In SM $b_i^{(SM)} = \{41/10, -19/6, -7\}$, $i = 1, 2, 3$ and the SM without any new physics up to the GUT mass scale M_{GUT} ("grand desert") do not unify three coupling constants at any mass scale (see the lines 1 in Fig.3). But such a unification can be possible if an intermediate new physics below M_{GUT} (such as the four color symmetry physics with mass scale M_c) is assumed. For example in the model under consideration in the case of the scalar sector containing, for simplicity, only the standard

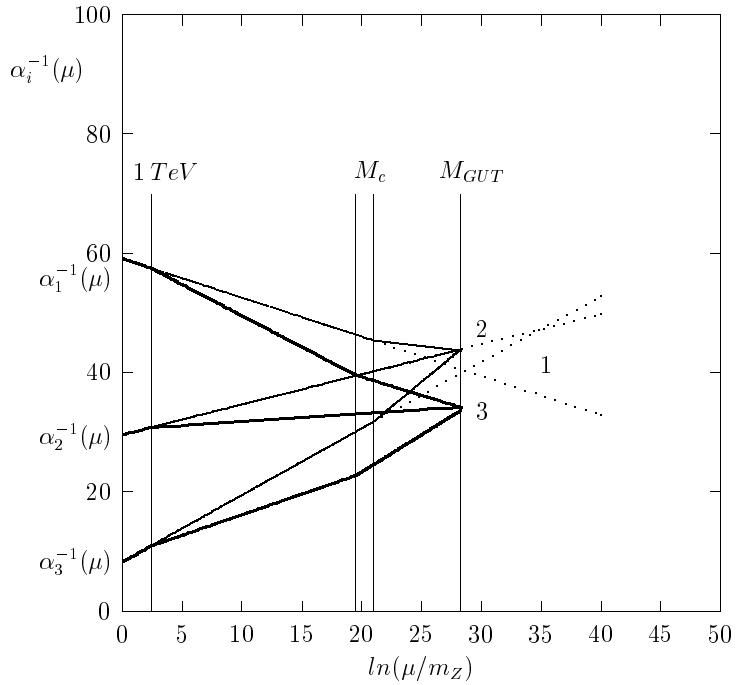

Figure 2: Gauge coupling constant unification in the GUT models with the four color symmetry (FCS), (1)–SM, (2)–FCS without scalar doublets, (3)–FCS with the light scalar doublets.

Higgs doublet and the (4,1,1) multiplet $\Phi^{(1)}$ with VEV $\eta_1 \sim M_c \sim 10^{11} \div 10^{12}\ GeV$ we obtain for $\mu > M_c$ the resulting contributions $\Delta b_i^{(V+\Phi^{(1)})} = \{-8/3,\ 0,\ -7/2\}$ from the vector leptoquarks and from the multiplet $\Phi^{(1)}$ so that all three coupling constants do converge in one point at $M_{GUT} \sim 10^{14} \div 10^{15}\ GeV$ with $\alpha_3(M_{GUT}) = \alpha_2(M_{GUT}) = \alpha_1(M_{GUT}) \equiv \alpha_{GUT} \sim 0.023$ (the lines 2 in Fig.3). The account of the scalar leptoquark and scalar gluon doublets with the masses of order of 1 TeV or less gives for $\mu > 1\,TeV$ the additional contributions $\Delta b_i^{(S+F)} = \{37/15,\ 7/3,\ 8/3\}$ so that in this case all three coupling constants $\alpha_i(\mu)$ do also converge in one point if $M_c \sim 10^{10} \div 10^{11}\ GeV$ and $M_{GUT} \sim 10^{14} \div 10^{15}\ GeV$ with $\alpha_{GUT} \sim 0.029$ (the lines 3 in Fig.3). As seen the presence of the relatively light scalar leptoquark and scalar gluon doublets (with mases below 1 TeV) lowers the four color symmetry mass scale M_c and increases the value of the unified coupling constant α_{GUT}, leaving the GUT mass scale M_{GUT} practically unchanged.

In conclusion we can say that the existence of the relatively light scalar leptoquarks and scalar gluons (with masses of order of 1 TeV or less) is consistent with the current experimental data on S, T, U, the more light particles (with masses below 400 GeV) even slightly improve the fit.

In particular the scalar leptoquarks with the masses of order of $m_{scalar}^{lower} < 300\ GeV$ are consistent with current data on S, T, U for $m_H = 115(300)\ GeV$ with $\chi^2 < 3.1(3.2)$ (in comparison with $\chi^2 = 3.5(5.0)$ of the SM). The lightest scalar gluon in this case is expected to lie below 850(720) GeV.

We emphasize the possible significance of such particles in the top-quark physics at LHC.

Acknowledgments

The author is grateful to Organizing Commitee of the International Seminar "Quarks-2002" for possibility to participate in this Seminar. The work was supported by the Russian Foundation for Basic Research under grant 00-02-17883.

References

[1] J.C. Pati and A. Salam, Phys. Rev. D10 (1974) 275.

[2] E.M. Freire, Phys. Rev. D43 (1991) 209.

[3] G. Senjanovic, A. Sokorac, Z.Phys. C20 (1983) 255.

[4] R.R. Volkas, Phys. Rev. D53 (1996) 2681.

[5] A.D. Smirnov, Phys. Lett. B346 (1995) 297.

[6] A.D. Smirnov, Yad. Fiz. 58 (1995) 2252, Phys. of At. Nucl. 58 (1995) 2137.

[7] R. Foot, Phys. Lett. B420 (1998) 333.

[8] R. Foot, G. Filewood, Phys. Rev. D60 (1999) 115002.

[9] T.L. Yoon, R. Foot, Phys. Rev. D65 (2002) 015002,hep-ph/0105101.

[10] A. Blumhofer, B. Lampe, Eur. Phys. J. C7 (1999), 141.

[11] W. Buchmüller,R. Rückl, D. Wyler, Phys. Lett. B191 (1987) 442.

[12] J.L. Hewett, T.G. Rizzo, Phys. Rev. D56 (1997) 5709.

[13] A.V. Povarov, A.D.Smirnov, Yad. Fiz. 64 (2001) 78, Phys. At. Nucl. 64 (2001) 74.

[14] M.E. Peskin and T. Takeuchi, Phys. Rev. D46 (1992) 381.

[15] Particle Data Group: D.E. Groom et al., Eur. Phys. J. C15 (2000) 1 and 2001 partial update for edition 2002 (URL:http://pdg.lbl.gov).

[16] A.D. Smirnov, Phys. Lett. B431 (1998) 119.

[17] A.D. Smirnov, Yad. Fiz. 64 (2001) 367, Phys. At. Nucl. 64 (2001) 318.

[18] A.D. Smirnov, Phys. Lett. B531 (2002) 237.

[19] J.K.Mizukoshi, O.J.P.E'boli and M.C.Gonzale'z-Garci'a, Nucl.Phys. B443 (1995) 20.