Mass limits for scalar leptoquark and scalar gluon doublets from current data on S, T, U

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Abstract

The contributions into radiative correction parameters S, T, U from the scalar leptoquark and scalar gluon doublets of the minimal four color symmetry model are analysed in comparision with the curent experimental data on S, T, U. It is shown that the existence of the relatively light scalar leptoquark and scalar gluon doublets (with masses below 1 TeV) is consistent with current data on S, T, U improves in comparison with the SM the agreement of the model with the current data on S, T, U and can relax the SM upper limit on the mass of Higgs boson.

1 Introduction

The search for a new physics beyond the Standard Model (SM) is now one of the aims of the high energy physics. One of the new physics can be induced by the possible four color symmetry treating leptons as quarks of the fourth color [1]. The four color symmetry can be unified with the SM by the gauge group

$$G_{new} = G_c \times SU_L(2) \times U_R(1)$$

where G_c is the group of the four color symmetry.

In dependence on its type the four color symmetry predicts the new gauge fields

$$\begin{aligned}
G_c &= SU_V(4) \;\; \Rightarrow \;\; V,\ Z', \\
G_c &= SU_L(4) \times SU_R(3) \;\; \Rightarrow \;\; V^L,\ G^{(A)},\ Z', \\
G_c &= SU_L(3) \times SU_R(4) \;\; \Rightarrow \;\; V^R,\ G^{(A)},\ Z', \\
G_c &= SU_L(4) \times SU_R(4) \;\; \Rightarrow \;\; V^L,\ V^R,\ G^{(A)},\ Z'_1,\ Z'_2,
\end{aligned}$$

where V, V^L, V^R, are vector and chiral gauge leptoquarks, $G^{(A)}$ is an axigluon and Z, Z'_1, Z'_2 are extra neutral Z' bosons.

The most stringent lower mass limits for the gauge leptoquarks are the indirect mass limits resulted from $K^0_L \to e^{\mp}\mu^{\pm}$ decay which in the case of zero fermion mixing are [2–6]

$$m_V^{lower} = 2000\ TeV, \tag{1}$$

$$m_{V^L}^{lower} = 260\ TeV. \tag{2}$$

It should be noted however that the four color symmetry allows also the existence of scalar leptoquarks and such particles have been phenomenologically introduced in ref. [7] and have been discussed in a number of papers.

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The experimental lower mass limits for the scalar leptoquarks from their direct search are [8]

$$\begin{array}{llll} \text{1st generation} & \text{2nd generation} & \text{3rd generation} & \\ m_{LQ} > 256\,\text{GeV}, & 251\,\text{GeV}, & 148\,\text{GeV}, & 153\,\text{GeV}\ [9] \\ Br(eq)=1, & Br(\mu q)=1, & Br(\nu b)=1, & Br(\tau b)=1; \\ m_{LQ} > 234\,\text{GeV}, & 204\,\text{GeV} & & \\ Br(eq)=0.5, & Br(\mu q)=0.5. & & \end{array}$$

The indirect mass limits for the scalar leptoquarks depend on the magnitude of the scalar leptoquark coupling constants with fermions which under phenomenological introduction are arbitrary so that only the relation of these coupling constants to the leptoquark masses h/m_S can be restricted experimentally.

Nevertheless there is the situation when the typical magnitudes of the scalar leptoquark coupling constants with fermions are known. Indeed, in the case of Higgs mechanism of the quark-lepton mass splitting the four color symmetry of the vector type (Minimal Quark–Lepton Symmetry Model – MQLS model [10, 11]) predicts the $SU(2)_L$ scalar leptoquark and scalar gluon doublets $S_a^{(\pm)}$, F_a with Yukawa coupling constants which are (due their Higgs origin) proportional to the ratios m_f/η of the fermion masses m_f to the SM VEV η.

$$\text{MQLS - model} = \begin{cases} G_{new} = SU_V(4)\times SU_L(2)\times U_R(1)\ + \\ \text{the Higgs mechanism of fermion mass generation} \\ \text{(including the quark–lepton mass splittings)} \end{cases}$$

$$\text{MQLS - model} \ \Rightarrow \begin{pmatrix} S_{1\alpha}^{(+)} \\ S_{2\alpha}^{(+)} \end{pmatrix}, \begin{pmatrix} S_{1\alpha}^{(-)} \\ S_{2\alpha}^{(-)} \end{pmatrix}, \begin{pmatrix} F_{1k} \\ F_{2k} \end{pmatrix}, \begin{pmatrix} \Phi'_1 \\ \Phi'_2 \end{pmatrix}, \begin{pmatrix} \Phi_1^{(SM)} \\ \Phi_2^{(SM)} \end{pmatrix},$$

$\alpha = 1, 2, 3,\ k = 1, 2, ..., 8$ – $SU_c(3)$–color indices.

$$Q_{em}: \quad \begin{pmatrix} 5/3 \\ 2/3 \end{pmatrix}, \begin{pmatrix} 1/3 \\ -2/3 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \end{pmatrix}.$$

$$h \sim m_f/\eta.$$

As a result the Yukawa coupling constants of the scalar keptoquarks $S_a^{(\pm)}$ are known (up to mixing parameters), which gives the possibility to estimate the possible effects induced by these particles. The indirect mass limits for the scalar leptoquarks $S_a^{(\pm)}$ from $K_L^0 \to e^{\mp}\mu^{\pm}$ decays have been investigated in refs. [5,6] and unlike the gauge leptoquark mass limits (1), (2) occurred to be weak, of order of the direct mass limits for the scalar leptoquarks.

An another source of mass limits for new particle is the analysis of their conributions into the radiative corrections. As is known in the case when 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 [12]. The first analysis of the contributions into S, T, U from scalar leptoquark doublets $S_a^{(\pm)}$ [13, 14] and of those from scalar gluon doublets F_a [15, 16] showed that these particles can be light, with masses of order of $1\,TeV$ or less. It is interesting now what can we say about the masses of these scalar doublets taking into acount the current experimental data on S, T, U which are [8]

$$\begin{aligned} S_{new}^{exp} &= -0.13 \pm 0.10(-0.08), \\ T_{new}^{exp} &= -0.13 \pm 0.11(+0.09), \\ U_{new}^{exp} &= \ \ 0.20 \pm 0.12(+0.01), \end{aligned} \qquad (3)$$

where the central values assume $m_H = 117\ GeV$ and the change for $m_H = 300\ GeV$ is shown in parentheses. Below I will be discussing the limits on the masses of scalar leptoquark doublets $S_a^{(\pm)}$ and of scalar gluon doublets F_a which are imposed by current experimental data (3).

2 Contributions into S, T, U from scalar leptoquark and scalar gluon doublets

The S-, T-, U- parameters of Peskin and Takeuchi are defined as [12]

$$\begin{aligned}
\alpha S &= 4 s_W c_W [s_W c_W (\Pi'_{ZZ}(0) - \Pi'_{AA}(0)) - ({c_W}^2 - {s_W}^2)\Pi'_{ZA}(0)], \\
\alpha T &= \frac{1}{{c_W}^2 {m_Z}^2}[\Pi_{WW}(0) - {c_W}^2 \Pi_{ZZ}(0)], \\
\alpha U &= 4{s_W}^2[\Pi'_{WW}(0) - {c_W}^2 \Pi'_{ZZ}(0) - {c_W}^2 \Pi'_{AA}(0) - 2 c_W s_W \Pi'_{ZA}(0)],
\end{aligned}$$

where $\Pi^{\mu\nu}_{XY}(k^2) = g^{\mu\nu}\Pi_{XY}(k^2) + (k^\mu k^\nu - terms)$ are the self energy functions of X-, Y-fields, $\Pi_{XY}(k^2) = \Pi_{XY}(0) + k^2 \Pi'_{XY}(0) + ...$, X, Y are A_μ-,Z_μ- and $W^\pm_\mu$-fields.

The S, T, U parameters are normalized so that in the SM (i.e. in the case of absence of any New Physics) S, T, U must be equal to zero:

$$S_{new} = 0, T_{new} = 0, U_{new} = 0.$$

The contribution of scalar leptoquark and scalar gluon doublets into S, T, U in general case have been calculated in refs. [13–16]. In general case the scalar leptoquark contributions into S, T, U are rather complicated because of the possible scalar leptoquark mixing

$$S_{2\alpha}^{(+)} = \sum_{m=0}^{3} c_m^{(+)} S_m, \qquad \overset{*}{S}{}_2^{(-)} = \sum_{m=0}^{3} c_m^{(-)} S_m$$

and because of existence of the goldstone mode S_0.

Below we consider the case of zero 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

$$S^{(+)} = \begin{pmatrix} S_1^{(+)} \\ S_2^{(+)} \end{pmatrix}, S^{(-)} = \begin{pmatrix} S_1^{(-)} \\ S_2^{(-)} \end{pmatrix} \tag{4}$$

are the physical states and their contributions into S, T, U take the simplest form

$$\begin{aligned}
S^{(LQ)} &= \frac{n_c}{12\pi}\Big\{ - Y_+^{SM} \ln \frac{m_+^2}{m_1^2} - Y_-^{SM} \ln \frac{m_-^2}{m_2^2} \Big\}, \\
T^{(LQ)} &= \frac{n_c}{16\pi s_W^2 c_W^2 m_Z^2}\Big\{ f_1(m_+, m_1) + f_1(m_-, m_2) \Big\} \geq 0, \\
U^{(LQ)} &= \frac{n_c}{12\pi}\Big\{ f_2(m_+, m_1) + f_2(m_-, m_2) \Big\} \geq 0,
\end{aligned}$$

where

$$\begin{aligned}
f_1(m_1, m_2) &= {m_1}^2 + {m_2}^2 - \frac{2 m_1^2 m_2^2}{{m_1}^2 - {m_2}^2} \ln \frac{m_1^2}{m_2^2} \geq 0\,, \\
f_2(m_1, m_2) &= -\frac{5{m_1}^4 + 5{m_2}^4 - 22{m_1}^2{m_2}^2}{3({m_1}^2 - {m_2}^2)^2} + \\
&+ \frac{{m_1}^6 - 3{m_1}^4{m_2}^2 - 3{m_1}^2{m_2}^4 + {m_2}^6}{({m_1}^2 - {m_2}^2)^3} \ln \frac{m_1^2}{m_2^2} \geq 0\,,
\end{aligned}$$

$n_c = 3$, $Y^{SM}_{\pm} = 1 \pm 4/3$ and $m_+ = m_{S_1^{(+)}}$, $m_- = m_{S_1^{(-)}}$, $m_{1,2} = m_{S_2^{(+)},S_2^{(-)}}$ are the scalar leptoquark masses. The contributions $T^{(LQ)}$ and $U^{(LQ)}$ from the scalar leptoquark doublets (4) in the case without scalar leptoquark mixing are positive and they are equal to zero in the case of equal masses inside the doublets.

The scalar gluon doublets can be written as

$$F_j = \begin{pmatrix} F_{1j} \\ (\phi_{1j} + i\phi_{2j})/\sqrt{2} \end{pmatrix}, \tag{5}$$

where the charged fields F_{1j} and the neutral fields $\phi_{1j}, \phi_{2j}, j = 1, 2, ..., 8$ are the mass eigen state fields.

The scalar gluon doublets (5) give the next contributions into S, T, U

$$\begin{aligned}
S^{(F)} &= -\frac{k_F}{24\pi}\left\{ \ln\frac{m^2_{F_1}}{m^2_{\phi_1}} + \ln\frac{m^2_{F_1}}{m^2_{\phi_2}} - f_2(m_{\phi_1}, m_{\phi_2}) \right\}, \\
T^{(F)} &= \frac{k_F}{32\pi {c_W}^2 {s_W}^2 {m_Z}^2}\left\{ f_1(m_{F_1}, m_{\phi_1}) + f_1(m_{F_1}, m_{\phi_2}) - f_1(m_{\phi_1}, m_{\phi_2}) \right\}, \\
U^{(F)} &= \frac{k_F}{24\pi}\left\{ f_2(m_{F_1}, m_{\phi_1}) + f_2(m_{F_1}, m_{\phi_2}) - f_2(m_{\phi_1}, m_{\phi_2}) \right\},
\end{aligned}$$

where $k_F = 8$. The contributions $T^{(F)}$ and $U^{(F)}$ are not positive definite and they are negative if m_{F_1} is between m_{ϕ_1} and m_{ϕ_2}.

3 Numerical results and discussion

We have analysed the total contributions

$$S = S^{(LQ)} + S^{(F)}, \;\; T = T^{(LQ)} + T^{(F)}, \;\; U = U^{(LQ)} + U^{(F)}$$

from the scalar leptoquark and scalar gluon doublets in dependence on the masses of these particles. The masses of the scalar leptoquark and scalar gluon doublets are generated by the Higgs mechanism of the symmetry breaking from the scalar potential

$$V(\Phi^{(SM)}, S^{(+)}, S^{(-)}, F) \;\geq\; 0$$

including the interactions of these doublets with the standard Higgs doublet. For stability of the vacuum the coupling constants in the scalar potential are supposed to satisfy some conditions ensuring the positiveness of the scalar potential.

We vary the parameters in the scalar potential in such a way that the coupling constants in scalar potential do not exceed some maximal value λ_{max}

$$\lambda_i \leq \lambda_{max}$$

ensuring the validity of perturbation theory and the scalar leptoquark and scalar gluon masses do not go down some lower limit m^{lower}_{scalar}

$$m_1, m_2, m_{\pm}, m_{F_1}, m_{\phi_1}, m_{\phi_2} \geq m^{lower}_{scalar}$$

which is the mass of the lightest scalar particle. In the 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 $\lambda_{max}/4\pi = 0.1 - 0.3$.

Varying the parameters in the scalar potential 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 (3).

After minimization χ^2_{min} depends on the lower limit m^{lower}_{scalar} on the masses of the scalar leptoquarks and scalar gluons and on the upper limit λ_{max} on the coupling constants of the scalar potential.

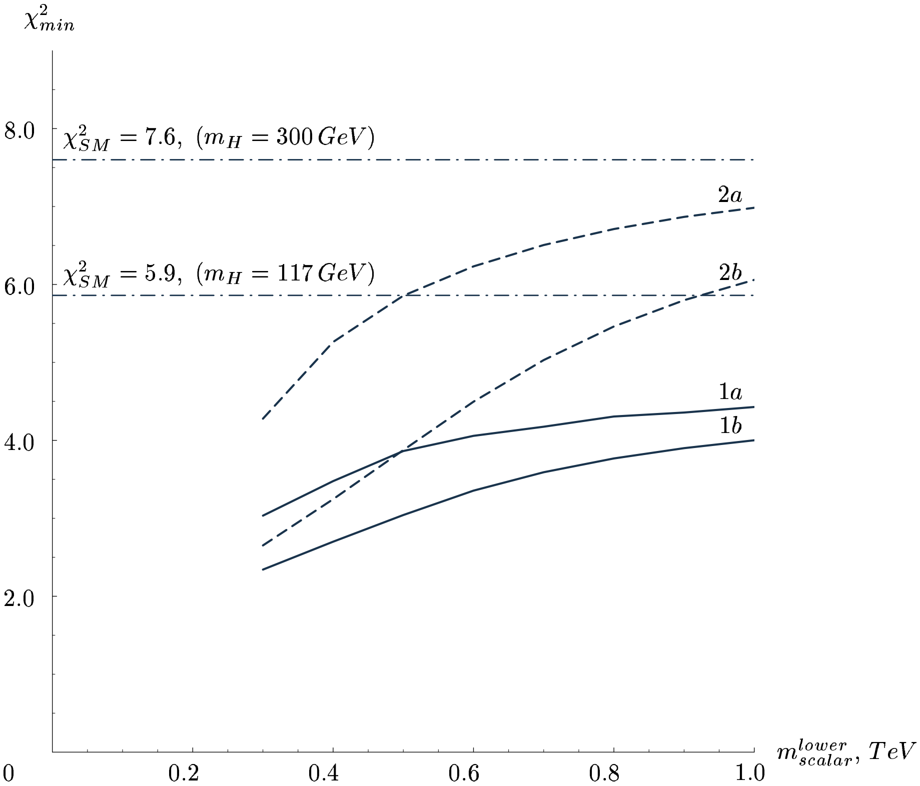

Figure 1: $\chi^2_{min}(m^{lower}_{scalar}, \lambda_{max})$ as a function of the lower limit m^{lower}_{scalar} on the scalar doublet masses for 1) $m_H = 117\ GeV$, 2) $m_H = 300\ GeV$ at $a)\ \lambda_{max} = 1.0,\ b)\ \lambda_{max} = 4.0$.

The Fig.1 shows $\chi^2_{min}(m^{lower}_{scalar}, \lambda_{max})$ as a function of the lower limit m^{lower}_{scalar} for $m_H = 117\ GeV$ (the curves 1) and for $m_H = 300\ GeV$ (the curves 2) at $\lambda_{max} = 1.0(4.0)$ (the curves $a(b)$). The horizontal lines denote $\chi^2_{SM} = 5.9$ and $\chi^2_{SM} = 7.6$ of the compatibility of the SM zero values of S, T, U with the experimental data (3) at $m_H = 117\ GeV$ and $m_H = 300\ GeV$ respectively.

As seen from the Fig.1 the lower limit m^{lower}_{scalar} on the masses of the scalar leptoguarks and of the scalar gluons is allowed by data (3) to be of order of 1 TeV or less. It is interesting that in both cases the possible existence of such light particles agree with the data (3) even better than in the SM and can relax the SM upper limit on the mass of Higgs boson.

For example for $\lambda_{max} = 1.0$, $m^{lower}_{scalar} = 400\ GeV$ the scalar leptoquarks and gluons with the masses

$$m_{S_1^{(+)}} = 440\,GeV,\quad m_{S_1^{(-)}} = 400\,GeV,\quad m_{F_1} = 460\,GeV,$$
$$m_{S_2^{(+)}} = 400\,GeV,\quad m_{S_2^{(-)}} = 420\,GeV,\quad m_{\phi_1} = 480\,GeV,\quad m_{\phi_2} = 400\,GeV$$

give the contributions

$$\begin{aligned}
S^{(LQ)} &= -0.03, \quad T^{(LQ)} = 0.08, \quad U^{(LQ)} = 5.5 \cdot 10^{-4}, \\
S^{(F)} &= -0.01, \quad T^{(F)} = -0.21, \quad U^{(F)} = -1.2 \cdot 10^{-3}, \\
S &= -0.05, \quad T = -0.13, \quad U = 6.6 \cdot 10^{-4},
\end{aligned}$$

which agree with

$$S^{exp}_{new} = -0.13 \pm 0.10, \; T^{exp}_{new} = -0.13 \pm 0.11, \; U^{exp}_{new} = 0.20 \pm 0.12$$

for $m_H = 117\ GeV$ with $\chi^2 = 3.5$ (in comparison with $\chi^2_{SM} = 5.9$).

In a similar way for $\lambda_{max} = 1.0$, $m^{lower}_{scalar} = 400\ GeV$ the scalar leptoquarks and gluons with the masses

$$\begin{aligned}
&m_{S_1^{(+)}} = 440\,GeV, \quad m_{S_1^{(-)}} = 400\,GeV, \quad m_{F_1} = 520\,GeV, \\
&m_{S_2^{(+)}} = 400\,GeV, \quad m_{S_2^{(-)}} = 440\,GeV, \quad m_{\phi_1} = 540\,GeV, \quad m_{\phi_2} = 440\,GeV
\end{aligned}$$

give the contributions

$$\begin{aligned}
S^{(LQ)} &= -0.04, \quad T^{(LQ)} = 0.14, \quad U^{(LQ)} = 9.5 \cdot 10^{-4}, \\
S^{(F)} &= -0.03, \quad T^{(F)} = -0.20, \quad U^{(F)} = -9.5 \cdot 10^{-4}, \\
S &= -0.06, \quad T = -0.06, \quad U = 3.4 \cdot 10^{-6},
\end{aligned}$$

which agree with

$$S^{exp}_{new} = -0.21 \pm 0.10, \; T^{exp}_{new} = -0.04 \pm 0.11, \; U^{exp}_{new} = 0.21 \pm 0.12$$

for $m_H = 300\ GeV$ with $\chi^2 = 5.3$ (in comparison with $\chi^2_{SM} = 7.6$).

4 Conclusion

- The contributions into radiative correction parameters S, T, U from the scalar leptoquark and scalar gluon doublets predicted by the four color symmetry with Higgs mechanism of the quark–lepton mass splitting are discussed in comparison with the curent experimental data on S, T, U .
- It is shown that the existence of the relatively light scalar leptoquark and scalar gluon doublets (with masses below 1 TeV)
- is consistent with current experimental data on S, T, U (this conclusion is stable under variations of the experimental values of S, T, U),
- gives the negative values to S and T parameters with improving (in comparison with the SM) the agreement of the model with the current experimental data on S, T, U and
- can relax the SM upper limit on the mass of Higgs boson.

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