# Bounds on Scalar Leptoquark Masses from S, T, U in the Minimal Model With the Four-Color Symmetry

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**Abstract**

The contributions into radiative correction $S$, $T$, $U$ parameters from the scalar leptoquarks are considered in frame of the minimal model with the four-color gauge symmetry. Taking the current experimental data on $S$, $T$, $U$ into account the bounds on the scalar leptoquark masses are obtained and discussed. In particular, it is shown that the current experimental data on $S$, $T$, $U$ allow the existence of relatively light scalar leptoquark with electric charge 2/3.

The search for a new physics beyond the Standard Model (SM) is now one of the aims of the high energy physics. It is interesting to know what kind of the new physics can manifest itself as the energy of the colliding particles increase. What are the possible manifestations of such new physics at attainable energies? One of the possible variants of the new physics beyond the SM can turn out to be the variant induced by the possible four-color symmetry [1] between quarks and leptons.

The main feature of the four-color gauge symmetry is the prediction of the vector leptoquarks with the masses of about the mass scale $M_c$ of the four-color symmetry breaking. In the models induced by the grand unification ideas the four-color symmetry can manifest itself as an intermediate

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symmetry with mass scale $M_c$ expected to be usually very high. For instance, in $SO(10)$ model it is of about $M_c \sim 10^{12}\ GeV$ [2] but it can be essentially lowered up to $M_c \sim 10^5 - 10^6\ GeV$ by appropriate scheme of the symmetry breaking [3]. In the models regarding the four-color symmetry as a primary symmetry [4, 5, 6, 7, 8] the lower limit on the mass scale $M_c$ is determined mainly by the low energy experimental data and it can be essentially lower, for example, of about $1000\,TeV$ [6] or about 100 $TeV$ or slightly less [4, 5] or even of about $1\,TeV$ [7, 8].

The four-color symmetry can manifest itself not only by the vector leptoquark physics but also due to the scalar leptoquarks. Some of the scalar leptoquarks should have $SU(2)-$ doublet structure and, hence, can manifest themselves in the oblique radiative corrections, in particular, affecting the $S, T, U$ parameters of Peskin and Takeuchi [9]. Taking into account the rather stringent current experimental limits on $S, T, U$ it is interesting to know what bounds on the scalar leptoquark masses can be extracted from the current experimental data on $S, T, U$. For this purpose it is interesting to know the effect of the scalar leptoquarks on $S, T, U$ in some simple gauge model predicting these particles.

In this talk I would like to consider the contributions into $S, T, U$ parameters from the scalar leptoquarks in frame of a minimal model with the four-color symmetry in comparison with the current experimental data on $S, T, U$ and to discuss the bounds on scalar leptoquark masses which can be extracted in this model from these data.

The minimal quark-lepton symmetry model ( MQLS-model ) [4, 5] to be used here as a minimal extension of the SM containing the four-color gauge symmetry is based on the gage group $SU_V(4) \times SU_L(2) \times U_R(1)$. The fermion sector of the model contains only the known fermions (quarks and leptons), whereas the gauge sector predicts the new gauge particles- vector leptoquarks $V^{\pm}$ with electric charge $\pm 2/3$ and an extra neutral $Z'-$boson.

The scalar sector of the model contains in general the four multiplets $\Phi^{(1)}$, $\Phi^{(2)}_a$, $\Phi^{(3)}_a$, $\Phi^{(4)}, a = 1, 2$ 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 VEV's $\eta_1$, $\eta_2$, $\eta_3$, $\eta_4$ respectively (the content of the multiplets and notations can be found in more detail in Refs.[10, 11]).

As regards the $S, T, U$ parameters the most intersting of these multiplets is the muliplet $\Phi^{(3)}$ which has been introduced to split the masses of quarks and leptons.This multiplet contains fifteen doublets which can be arranged into two scalar leptoquark doublets $S^{(+)}_{a\alpha}$ and $S^{(-)}_{a\alpha}$, $\alpha=1,2,3$ with the SM hypercharge $Y^{(SM)}$=7/3 and -1/3 respectively, eight scalar gluon doublets $F_{ja}$, j=1,2,...8 with $Y^{(SM)}$=1 and the doublet $\Phi^{(3)}_{15,a}$ which in admixture with $\Phi^{(2)}_{a}$ gives the SM doublet $\Phi^{(SM)}$ with SM VEV $\eta=\sqrt{\eta_2{}^2+\eta_3{}^2}=(\sqrt{2}G_F)^{-\frac{1}{2}}\approx$ 250 $GeV$ and an additional scalar doublet $\Phi'$.

In addition to the scalar leptoquark doublets $S^{(\pm)}_a$ of the multiplet $\Phi^{(3)}$ the multiplets $\Phi^{(1)}$ and $\Phi^{(4)}$ contain the singlet scalar leotoquarks $S^{(1)}$ and $S^{(4)}$ with electric charge 2/3 which give in admixture with $S^{(+)}_2$, $\overset{*}{S}{}^{(-)}_2$ the Goldstone mode $S_0$ and three mass eigenstate leptoqurk fields $S_1$, $S_2$, $S_3$. As a result in the unitary gauge we obtain, in general, five scalar leptoquarks: $S^{(+)}_1, S^{(-)}_1$ with electric charge 5/3 and 1/3 respectively and $S_{k\alpha}, k=1,2,3$ with electric charge 2/3.

The resulting contributions into $S,T,U$ from leptoquarks can be presented in the form [10, 11]

$$
\begin{aligned}
S^{(LQ)} &= \frac{n_c}{12\pi}\Bigg\{-\sum_{+,-}\sum_{k}|C^{(\pm)}_k|^2 Y^{SM}_{\pm}\ln\frac{m^2_{\pm}}{m^2_k}+\frac{1}{2}\sum_k\sum_l B_{kl}f_2(m_k,m_l)\\
&+\xi^2\Big[\sum_k|C_{1k}|^2\left(-12\frac{m^2_V f_1(m_k,m_V)}{(m^2_k-m^2_V)^2}+f_2(m_V,m_k)\right) \qquad (1)\\
&+\frac{1}{2}\sum_{+,-}\ln\frac{m^2_V}{m^2_{\pm}}-\frac{2}{3}\ln\frac{m^2_+}{m^2_-}\Big]\Bigg\},\\
T^{(LQ)} &= \frac{n_c}{16\pi s^2_W c^2_W m^2_Z}\Bigg\{\sum_{+,-}\sum_k|C^{(\pm)}_k|^2 f_1(m_\pm,m_k) \qquad (2)\\
&-\frac{1}{2}\sum_k\sum_l B_{kl}f_1(m_k,m_l)\\
&+\xi^2\sum_{+,-}\sum_k|C_{2k}|^2\Big[\frac{1}{2}\left(f_1(m_\pm,m_V)-f_1(m_k,m_V)\right)\\
&+4m^2_V f_3(m_\pm,m_k;m_V)\Big]\Bigg\},\\
U^{(LQ)} &= \frac{n_c}{12\pi}\Bigg\{\sum_{+,-}\sum_k|C^{(\pm)}_k|^2 f_2(m_\pm,m_k)-\frac{1}{2}\sum_k\sum_l B_{kl}f_2(m_k,m_l)
\end{aligned}
$$

$$+\xi^2 \sum_{+,-} \sum_k |C_{2k}|^2 \Big[ \frac{1}{2} \left( f_2(m_\pm, m_V) - f_2(m_k, m_V) \right) \tag{3}$$
$$-6m_V^2 \left( \frac{f_1(m_\pm, m_V)}{(m_\pm^2 - m_V^2)^2} - \frac{f_1(m_k, m_v)}{(m_k^2 - m_V^2)^2} \right) \Big] \Big\},$$

where

$$f_1(m_1, m_2) = {m_1}^2 + {m_2}^2 - \frac{2m_1^2 m_2^2}{{m_1}^2 - {m_2}^2} \ln \frac{m_1^2}{m_2^2}, \tag{4}$$

$$f_2(m_1, m_2) = -\frac{5{m_1}^4 + 5{m_2}^4 - 22{m_1}^2{m_2}^2}{3({m_1}^2 - {m_2}^2)^2} + \frac{{m_1}^6 - 3{m_1}^4{m_2}^2 - 3{m_1}^2{m_2}^4 + {m_2}^6}{({m_1}^2 - {m_2}^2)^3} \ln \frac{m_1^2}{m_2^2} \tag{5}$$

are well known functions and $f_3(m_1, m_2; m_V)$ is defined by equation

$$f_3(m_1, m_2; m_V) = \frac{m_1^2 m_2^2 \ln(m_1^2/m_2^2) + m_V^2(-m_1^2 \ln(m_1^2/m_V^2) + m_2^2 \ln(m_2^2/m_V^2))}{(m_1^2 - m_V^2)(m_2^2 - m_V^2)}. \tag{6}$$

Here

$$B_{kl} = |\overset{*}{C}{}_k^{(+)} C_l^{(+)} - \overset{*}{C}{}_k^{(-)} C_l^{(-)}|^2, \; C_k^{(\pm)} = \frac{1}{\sqrt{2}}(\sqrt{1-\xi^2} C_{1k} \pm C_{2k}), k, l = 1, 2, 3$$

$$\xi^2 = \frac{2}{3}\eta_3^2/(\eta_1^2/4 + \frac{2}{3}(\eta_3^2 + \eta_4^2)) = \frac{2}{3} g_4^2 \eta_3^2 / m_V^2,$$

$Y_\pm^{SM} = 1 \pm 4/3, n_c = 3, m_k = m_{S_k}, m_\pm = m_{S_1^{(\pm)}}$, $m_V$ is the vector leptoquark mass, $g_4$ is the $SU_V(4)$ - coupling constant. $C_{1k}, C_{2k}$ are two unit mutually orthogonal complex vectors. In general, the vectors $C_{1k}, C_{2k}$ can be parametrized by means of three mixing angles and three phases, for example, as

$$C_{1k} = \{c_{13}c_{12}, \quad c_{13}s_{12}e^{i\delta_{12}}, \quad s_{13}e^{i\delta_{13}}\},$$
$$C_{2k} = \{-c_{23}s_{12}e^{-i\delta 12} - s_{23}s_{13}c_{12}e^{i(-\delta_{13}+\delta_{23})},$$
$$c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i(-\delta_{13}+\delta_{12}+\delta_{23})}, \quad s_{23}c_{13}e^{i\delta_{23}}\},$$

where $c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}, \theta_{ij}, \delta_{ij}$ are the mixing angles and phases.

The contributions (1)-(3) into $S, T, U$ from the scalar leptoquarks have some special features.

Firstly, the contributions (2), (3) from the scalar leptoquarks into $T$ and $U$ are not positive definite due to the mixing between the scalar leptoquarks with electric charge 2/3. The mixing of the components of two scalar doublets as a possible mechanism for obtaining the negative $T$ and $U$ was pointed out in Ref.[12]. But in our case the $S_1 - S_2 - S_3$ -mixing is caused by the presence of Goldstone mode in the scalar leptoquark sector and this mixing is an intrinsic feature of the model.

Secondly, in the case of the degenerated scalar leptoquark masses $m_k = m_- = m_+ \equiv m_S$ the expression (1) gives the nonzero contributoin into $S^{LQ}$, i.e.

$$S^{LQ} \neq 0, T^{(LQ)} = 0, U^{(LQ)} = 0,$$

whereas the contributions from the ordinary scalar doublets in the case of all degenerated masses are known to be equal to zero (see, for example, Refs.[5, 10]).

Thirdly, the possible large (due to the large VEV's $\eta_1, \eta_4$) splitting of the scalar leptoquark masses gives the possibility for $S$ and $T$ to take the large values, positive or negative in dependence on the mass splitting and the mixing parameters.

We have carried out the numerical analysis of the contributions (1)-(3) using the responsible for a new physics experimental values of $S^{exp}_{new}, T^{exp}_{new}, U^{exp}_{new}$ [13]

$$S^{exp}_{new} = -0.28 \pm 0.19, T^{exp}_{new} = -0.20 \pm 0.26, U^{exp}_{new} = -0.31 \pm 0.54 \qquad (7)$$

by minimizing $\chi^2$ 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 $S, T, U$ are the leptoquark contributions (1)-(3) and $\Delta S, \Delta T, \Delta U$ are the experimental errows in (7).

In following, we assume for simplicity that $\theta_{13} = \theta_{23} = 0$. In this case the contributions (1)-(3) depend on the vector leptoquark mass $m_V$, parameter $\xi$ and on the four scalar leptoquark masses $m_+ = m_{5/3}, m_- = m_{1/3}, m_1 = m_{2/3}, m_2 = m'_{2/3}$ and one mixing angle $\theta_{12}$. Here indexes $5/3, 1/3, 2/3$ of the mass denote the electric charges of the corresponding scalar leptoquarks.

The dependence of $S^{(LQ)}, T^{(LQ)}, U^{(LQ)}$ on the large $m_V$ (of order of hundreds TeV) is slight because of the smallness of the parameter $\xi$. For definiteness we assume further that $m_V \sim 100\; TeV$ and $\xi \sim 10^{-4}$. The numerical analysis of the contributions (1)-(3) by minimizing $\chi^2$ at these values of $m_V$ and $\xi$ shows that,

firstly, $S^{(LQ)}, T^{(LQ)}, U^{(LQ)}$ and $\chi^2$ depend on the ratios of scalar leptoquark masses, for definiteness, on the ratios $\mu_{2/3} = m_{2/3}/m_{5/3}$, $\mu_{1/3} = m_{1/3}/m_{5/3}$, $\mu'_{2/3} = m'_{2/3}/m_{5/3}$ and,

secondly, the value of the mixing angle $\theta_{12} = 0$ is favored.

$\chi^2_{min}$ as a functions of each of the independent mass ratios are shown in Fig.1 at $\theta_{12} = 0$. Here $\chi^2_{min}(\mu)$ denotes the minimal value of $\chi^2$ obtained at fixed value $\mu$ of one of the mass ratios by minimizing $\chi^2$ over two other mass ratios. The doublets $\Phi'$ and $F_j$,$j = 1, 2, ..., 8$ are supposed to be degenerated.

It is seen from Fig.1 that experimental values (7) favor one scalar leptoquark $S_1$ with electric charge 2/3 to be the lightest one (the solid line) the scalar leptoquark $S_1^{(-)}$ with electric charge 1/3 to be slightly heavyer (the bold line) whereas the other scalar leptoquarks $S_2$ and $S_1^{(+)}$ with electric charges 2/3 (the dotted line) and 5/3 respectively to be the heavyest ones.

The Fig.2 shows the regions in the plane of the lightest masses $\mu_{2/3}$ and $\mu_{1/3}$ compatible with the data (7) at 95% CL and 90% CL (the inner regions bounded by the solid and bold lines respectively).

Some remarks resulting from the analysis of numerical calculations should be made.

1) The scalar leptoquarks improve the agreement of the experimental values (7) with the theory so that $\chi^2$ can be reduced from the value $\chi^2 = 3.1$ (i.e. 38% CL) of the SM to the value $\chi^2 \approx 0.22$ (i.e. 97% CL) in the model under consideration. For example, at the mass ratios near the values $\mu_{2/3} = 0.01$, $\mu_{1/3} = 0.10$, $\mu'_{2/3} = 0.96$ the formulas (1)-(3) give the values

$$S^{(LQ)} = -0.27, T^{(LQ)} = -0.20, U^{(LQ)} = -0.06 \tag{8}$$

which agree with (7) with $\chi^2 = 0.22$ (i.e. at 97% CL).

2) The attainment of the values (8) demands, however, a fine mutual fitting of the mass ratios near the values mentioned above as if there were some relation between the masses of the scalar leptoquarks. Possibly, such mass relation can arise as a result of the broken four-color symmetry implied here.

3) The account of the mass splitting of the doublets $\Phi'$ and $F_j$ modifies the result not essentially (by about 10%) preferring slightly the down neutral components of these doublets to be lighter than the up charged ones.

4) The existence of the salar leptoquark doublets allows the mass splittings of other doublets to be rather large. The arising in this case large positive contribution into $T$ from these doublets can be absorbed by the large negative contribution from the scalar leptoquark, which results in the values compatible with the experimental ones.

Recently a new analysis of the current electroweak data has been carried out in Ref.[14]. Using the results of Ref.[14] one can obtain

$$S_{new}^{exp} = -0.11 \pm 0.13, T_{new}^{exp} = -0.03 \pm 0.14, U_{new}^{exp} = 0.03 \pm 0.38 \qquad (9)$$

at $m_t = 175\, GeV$, $m_{H^0} = 300\, GeV$.

The contributions (1)-(3) have a large mass region compatible with these data even at more high CL. As an example the dotted curve in Fig.2 shows the region in plane of $\mu_{2/3}$, $\mu_{1/3}$ compatible with the data (9) at 99% CL.

It should be pointed out that both data (7) and (9) do not impose any lower limit on the mass $m_{2/3}$ of the scalar leptoquark $S_1$ with electric charge 2/3 (as seen, the solid line in Fig.1 goes down monotonically as $\mu_{2/3}$ decrease and the allowed regions in Fig.2 are open from the side of the small values of $\mu_{2/3}$ ). This gives the possibility for the mass $m_{2/3}$ (in contrast, for example, to $m_{5/3}$) to be light, perhaps to lie even not far from the SM mass scale. If this is the case the scalar leptoquark $S_1$ could manifest itself in experiments at moderate energies, in particular, through the $e^+ d \overset{*}{S}_1$ - coupling in $e^+p$ - collisions and, for this reason, the experimental search for this scalar leptoquark seems to be reasonable.

In conclusion I resume the results of the work.

1) The contributions into radiative correction parameters $S, T, U$ from the scalar leptoquarks are considered in the minimal gauge model with the four-color quark-lepton symmetry in comparison with the current experimental data on $S, T, U$.

2) It is shown that the contributions into $T$ and $U$ from the scalar leptoquark doublets are not positive definite due to the mixing between the scalar leptoquark fields with electric charge 2/3, which is caused by the existence of the Goldstone mode among these fields.

3) Using the current experimental limits on $S, T, U$ the numerical analysis of these contributions is carried out and the bounds on the scalar leptoquark

masses are obtained.In particular, it is shown that the current experimental data on $S, T, U$ allow the existence of the relatively light scalar leptoquark with electric charge 2/3. The search for this scalar leptoquark seems to be reasonable.

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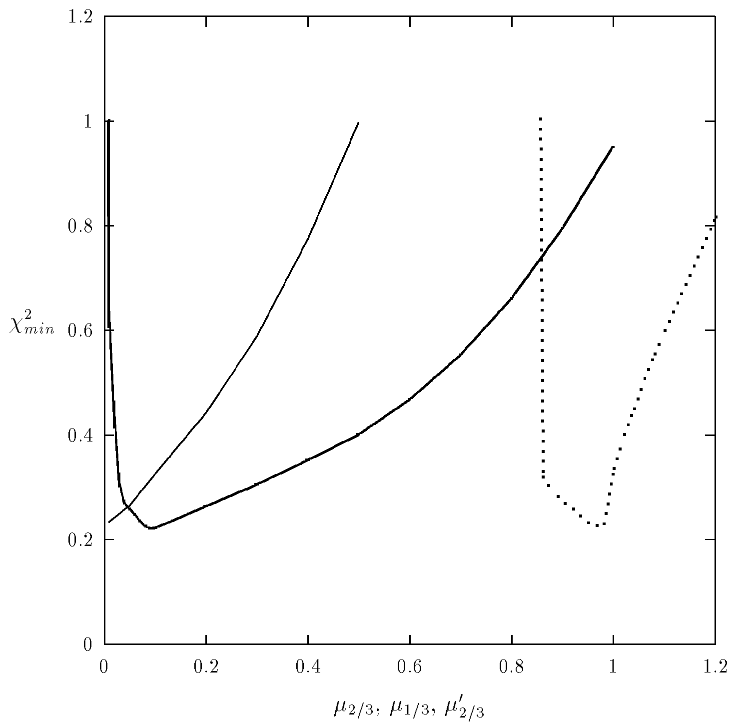


Figure 1: $\chi^2_{min}$ as a function of the scalar leptoquark mass ratios $\mu_{2/3} = m_{2/3}/m_{5/3}$ (the solid line), $\mu_{1/3} = m_{1/3}/m_{5/3}$ (the bold line), and $\mu'_{2/3} = m'_{2/3}/m_{5/3}$ (the dotted line).

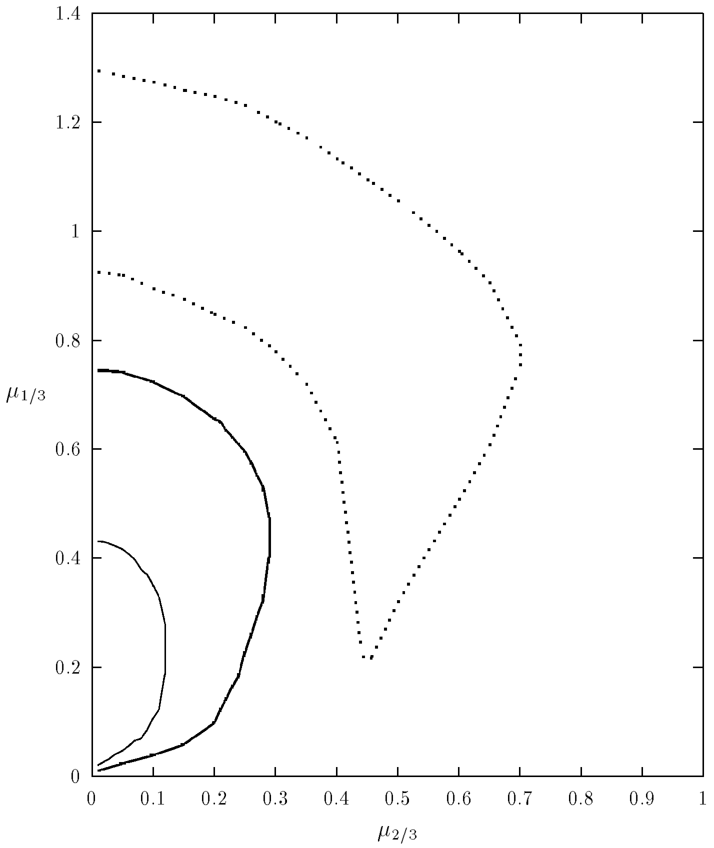


Figure 2: The regions in plane of mass ratios $\mu_{2/3} = m_{2/3}/m_{5/3}$, $\mu_{1/3} = m_{1/3}/m_{5/3}$ compatible with the data (7) at 95% CL (the solid line), at 90% CL (the bold line) and with the data (9) at 99% CL (the dotted line).