New Limits on Scalar Leptoquark Masses from S, T, U in the Minimal Model with the Four-Color Symmetry

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Abstract

The bounds on the scalar leptoquark masses from S-, T- ,U- parameters of Peskin - Takeuchi are investigated in frame of the minimal model with the four color symmetry with taking the scalar potential of the scalar leptoquark doublets interaction into account. Using the mass matrix and mixing angle resulted from this potential the new bounds on the scalar leptoquark masses are obtained from the current experimental data on S, T, U. It is shown that the light scalar leptoquarks (with masses below 1 TeV) are favored and improve the agreement of the experimental values of S,T,U with the theory.

The Standard Model of electroweak and strong interactions is now a good theoretical basis for investigation of the interactions of quark, leptons and gauge fields at energies of the modern colliders. Nevertheless it is interesting to know what kind of the new physics (supersymmetry, left- right symmetry etc.) can manifest itself if the energy of colliding particles increase.

One of the possible variants of the new physics beyond the SM can be the variant induced by the possible four-color symmetry [1] between quarks and leptons. This variant predicts the existence of the new gauge particles- vector leptoquarks with the masses of order of the mass scale M_c of the four-color symmetry breaking. The lower limit on M_c varies 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 [4–9].

It should be noted that the four-color symmetry can manifest itself not only by the vector leptoquark physics but also due to the scalar leptoquarks. It is interesting to know what region of the masses of scalar leptoquars is compatible with the current experimental data. The direct lower limit on the scalar leptoquark masses resulting from the unobservation of their direct production is about 250 GeV [10]. What limits on the scalar leptoquark masses can be extracted from the radiative corrections? It is known that if the masses m_{new} of the new particles are much larger than the mass m_Z of $Z-$boson ($m_{new} \gg m_Z$) the radiative corrections induced by the vacuum polarisation can be described by three parameters, for example by $S-, T-, U-$ parameters of Peskin and Takeuchi [11].

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The experiments give the bounds on the possible values of $S_{new}^{exp}, T_{new}^{exp}, U_{new}^{exp}$ induced by a new physics. The current bounds on these values are

$$\begin{aligned} S_{new}^{exp} &= -0.16 \pm 0.14 \ (-0.10), \\ T_{new}^{exp} &= -0.21 \pm 0.16 \ (+0.10), \\ U_{new}^{exp} &= -0.25 \pm 0.24 \ (+0.01), \end{aligned} \tag{1}$$

where the central values assume $m_H = m_Z$ and the change for $m_H = 300\ GeV$ is shown in parentheses [10]. Notice that in Standard Model we have, by definition, that

$$S_{new}^{SM} = 0, \quad T_{new}^{SM} = 0, \quad U_{new}^{SM} = 0. \tag{2}$$

The analysis shows that the scalar leptoquarks with the $SU_L(2)$-doublet structure contribute into S, T, U, which gives the possibillity to extract the bounds on the scalar leptoquark masses from $S_{new}^{exp}, T_{new}^{exp}, U_{new}^{exp}$ after calculations of their contributions into S, T, U. The general expressions for the contributions into S, T, U from the scalar leptoquarks have been found in frame of the minimal model with the four-color quark-lepton symmetry (MQLS-model) in ref.[12]. It was shown that some of the scalar leptoquarks can be relatively light and that these particles can even improve the agreement of the experimental values of S, T, U with the theory if the masses of the scalar leptoquarks and their mixing angles are regarded as free independent fit paramaters.

In the present paper we analyse the contributions into S, T, U from the scalar leptoquark doublets in MQLS-model in the case when the scalar leptoquark masses and mixing angle are generated by Higgs mechanism of symmetry breaking from the scalar potential of interactions of the scalar leptoquars with the standard Higgs doublet. This way of generating the scalar leptoquark masses seems to be the most natural one, and as it will be seen below it reduces the allowed region of the fitting parameters and leads to the new limits on the scalar leptoquark masses.

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 $\Phi_A^{(1)}$, $\Phi_a^{(2)}$, $\Phi_a^{(3)}$, $\Phi^{(4)}$, 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 $i = 1, 2 \ldots 15$ are the $SU_V(4)$ indexes and $a = 1, 2$ is the $SU_L(2)$ one.

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 $S_{a\alpha}^{(-)}$ 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 $\Phi_{15,a}^{(3)}$ which in admixture with $\Phi_a^{(2)}$ gives an additional scalar doublet Φ'_a and the SM doublet $\Phi_a^{(SM)}$ with SM VEV $\eta = \sqrt{\eta_2{}^2 + \eta_3{}^2} = (\sqrt{2}G_F)^{-1/2} \approx 250\ GeV$. All these scalar doublets contribute into S, T, U and the corresponding contributions have been calculated in ref.[12].

In general case the contributions $S^{(LQ)}$, $T^{(LQ)}$,$U^{(LQ)}$ into S-, T-, U from the leptoquarks depend on six masses, on the mixing parameters and on the small parameter $\xi^2 = \frac{2}{3}g_4^2\eta_3^2/m_V^2 \ll 1$, where m_V is the vector leptoquark mass. We neglect below the small parameter ξ and consider the simplest case of mixing

$$S^{(+)} = \left(\begin{array}{c} S_1^{(+)} \\ c\ S_2 + s\ S_1 \end{array} \right), S^{(-)} = \left(\begin{array}{c} S_1^{(-)} \\ -s\,\overset{*}{S}_2 + c\,\overset{*}{S}_1 \end{array} \right), \tag{3}$$

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

In this case the contributions $S^{(LQ)}$, $T^{(LQ)}$,$U^{(LQ)}$ of ref.[12] are simplified and take the form

$$\begin{aligned} S^{(LQ)} &= \frac{n_c}{12\pi}\Big\{ - Y_+^{SM}\Big[c^2\ln\frac{m_+^2}{m_2^2} + s^2\ln\frac{m_+^2}{m_1^2}\Big] \\ &\quad -Y_-^{SM}\Big[s^2\ln\frac{m_-^2}{m_2^2} + c^2\ln\frac{m_-^2}{m_1^2}\Big] + 4c^2s^2 f_2(m_1,m_2)\Big\}, \end{aligned} \tag{4}$$

$$\begin{aligned} T^{(LQ)} &= \frac{n_c}{16\pi s_W^2 c_W^2 m_Z^2}\Big\{c^2\Big[f_1(m_+,m_2) + f_1(m_-,m_1)\Big] \\ &\quad +s^2\Big[f_1(m_+,m_1) + f_1(m_-,m_2)\Big] - 4c^2s^2 f_1(m_1,m_2)\Big\}, \end{aligned} \tag{5}$$

$$\begin{aligned} U^{(LQ)} &= \frac{n_c}{12\pi}\Big\{c^2\Big[f_2(m_+,m_2) + f_2(m_-,m_1)\Big] \\ &\quad +s^2\Big[f_2(m_+,m_1) + f_2(m_-,m_2)\Big] - 4c^2s^2 f_2(m_1,m_2)\Big\}, \end{aligned} \tag{6}$$

where

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

$n_c = 3,\ Y_\pm^{SM} = 1 \pm 4/3,\ m_+ = m_{S_1^{(+)}} = m_{5/3},\ m_- = m_{S_1^{(-)}} = m_{1/3},\ m_{1,2} = m_{S_1,S_2} = m_{2/3,2/3'}$. Here indexes 5/3, 1/3, 2/3 of the mass denote the electric charges of the corresponding scalar leptoquarks.

In contrast to the case of the ordinary scalar or fermion doublets 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 $m_1 < m_+, m_- < m_2$. Notice that the central values of experimental value of T in (1) also has a tendency to be negative. 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.[13].

Let now the scalar leptoquark masses are generated from the scalar potential of the interactions of the scalar leptoquarks with the standard Higgs doublet by the Higgs mechanism of symmetry breaking. In general case the part of the scalar potential contributing into the scalar leptoquark masses can be written as

$$V(\Phi^{(SM)}, S) = \sum_{+,-} \Big[m_{\pm}^{(0)2} (\overset{+}{S}{}^{(\pm)} S^{(\pm)}) + \beta_{\pm} (\overset{+}{\Phi}{}^{(SM)} \Phi^{(SM)}) (\overset{+}{S}{}^{(\pm)} S^{(\pm)}) + \tag{7}$$
$$\gamma_{\pm} (\overset{+}{\Phi}{}^{(SM)} S^{(\pm)}) (\overset{+}{S}{}^{(\pm)} \Phi^{(SM)}) \Big] + \Big[\delta\, (\overset{+}{\Phi}{}^{(SM)} S^{(+)}) (\overset{+}{\Phi}{}^{(SM)} S^{(-)}) + h.c. \Big],$$

where $m_{\pm}^{(0)}2$ is the squared mass dimension parameter and $\beta,\ \gamma,\ \delta$ are the dimensionless coupling constants. After symmetry breaking the potential (7) gives the mass term of the scalar leptoquars in the form

$$V(\Phi^{(SM)}, S) = \sum_{+,-} m_{\pm}^{(0)2} (\overset{*}{S}{}_1^{(\pm)} S_1^{(\pm)}) + (S_2^{(+)}, \overset{*}{S}{}_2^{(-)})^* M \begin{pmatrix} S_2^{(+)} \\ \overset{*}{S}{}_2^{(-)} \end{pmatrix} + \ldots, \tag{8}$$

where $m_{\pm}^2 = m_{\pm}^{(0)2} + \beta_{\pm}\eta^2/2$ are the masses of the up scalar leptoquarks and

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} = \begin{pmatrix} m_+^2 + \gamma_+ \eta^2/2 & \overset{*}{\delta}\, \eta^2/2 \\ \delta\, \eta^2/2 & m_-^2 + \gamma_- \eta^2/2 \end{pmatrix} \tag{9}$$

is the mass matrix of the down ones.

For the case of real δ from the mass matrix (9) we have the masses of the scalar leptoquarks with electric charge 2/3 and mixing angle in the form

$$m^2_{2/3, 2/3'} = \left[M_{11} + M_{22} \mp \sqrt{(M_{11} - M_{22})^2 + 4M_{12}^2} \right] /2, \tag{10}$$
$$\tan 2\theta = -2M_{12}/(M_{11} - M_{22}), \tag{11}$$

where $m_{2/3}$ is the mass of the lightest scalar leptoquark and $m'_{2/3}$ is the mass of the heavyest one.

Regarding $m_{2/3}, m'_{2/3}, \gamma_+, \gamma_-, \delta$ as the fitting parameters we find the mass m_+, m_- and and the mixing angle from (9) - (11) and then calculate the contributions (4) - (6) of the scalar leptoquarks into S, T, U. Notice that for validity of the pertubation theory the coupling constants $\gamma_{\pm}$, δ in the potential (7) cannot be too large and this circumstance bounds the allowed region of the fitting masses and mixing angle in the formulas (4) - (6).

We have carried out the numerical analysys of the contributions (4) - (6) using the responsible for a new physics experimental values (1) by minimizing 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 S, T, U are the scalar leptoquark contributions (4) - (6) and $\Delta S, \Delta T, \Delta U$ are the experimental errors in (1). Notice that the SM values (2) agree with the experimintal ones (1) at $\chi^2 = 5.1$ and at $\chi^2 = 4.1$ for $m_H = 300\, GeV$ and for $m_H = m_Z$ respectively.

Minimizing χ^2 with S, T, U from (4) - (6) by variating the mass $m'_{2/3}$ and the parameters γ_+, γ_- under fixed $m_{2/3}$ and δ we have obtained $\chi^2_{min}(m_{2/3},\, \delta)$ in dependence on the mass $m_{2/3}$ of the lightest scalar leptoquar and on the parameter δ with slight dependence of χ^2 on γ_+, γ_-.

χ^2_{min} as the functions on the mass $m_{2/3}$ of the lightest scalar leptoquark at δ = 0.5, 1.0, 1.5 are shown in Fig.1 and Fig.2 for $m_H = 300\, GeV$ and $m_H = m_Z$ respectively.

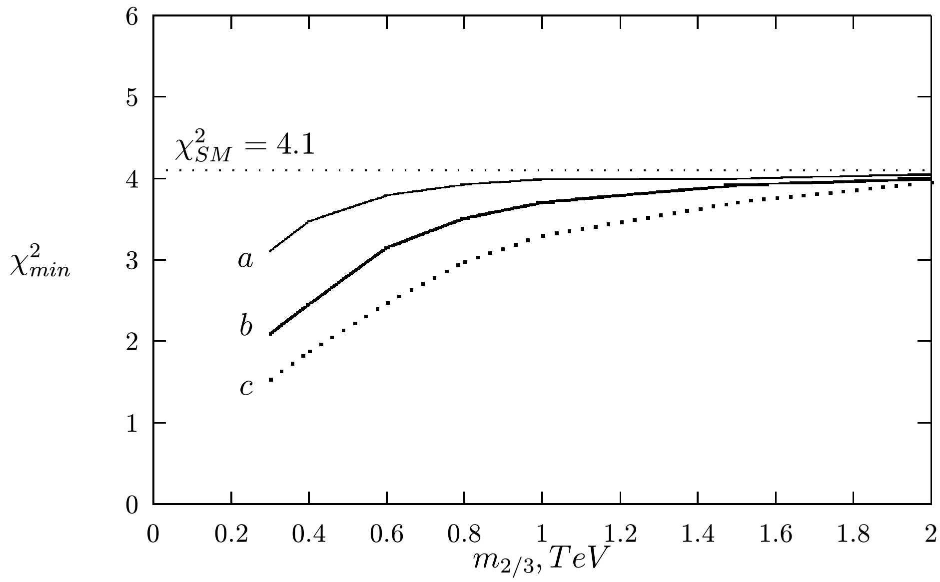

Figure 1: χ^2_{min} as a function of the mass $m_{2/3}$ of the lightest scalar leptoquark at $m_H = 300\, GeV$ and at $a)\, \delta = 0.5,\ b)\, \delta = 1.0,\ c)\, \delta = 1.5$.

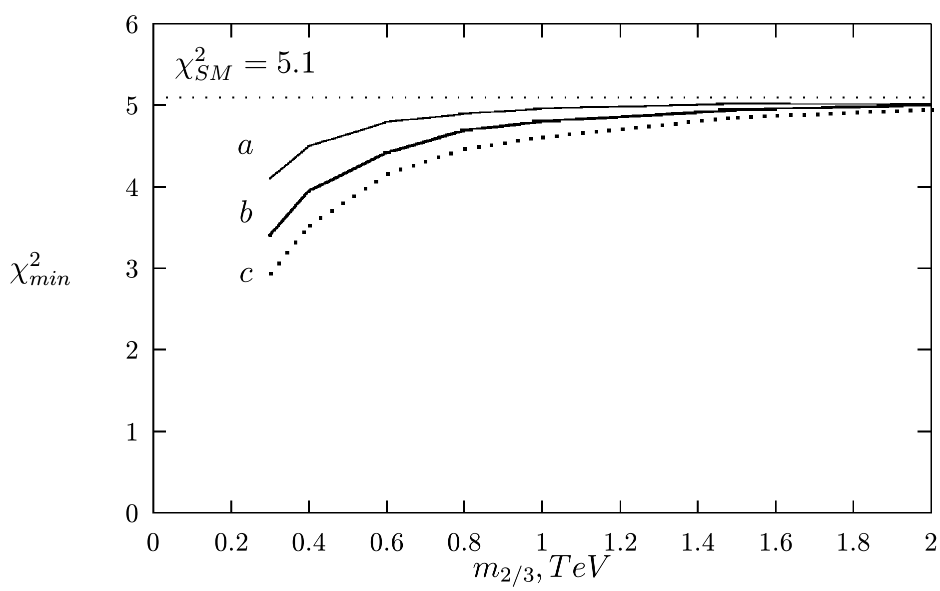

Figure 2: χ^2_{min} as a function of the mass $m_{2/3}$ of the lightest scalar leptoquark at $m_H = m_Z$ and at $a)\, \delta = 0.5,\ b)\, \delta = 1.0,\ c)\, \delta = 1.5$.

We see that the relatively light scalar leptoquarks (with the masses of order 1 TeV or less) are not only compatible with the experimental data on S, T, U but also can even improve the agreement of these data with theory.

For example for $\delta = 1$ and

$$m_{2/3} = 300\,GeV, \quad m_{1/3} = 350\,GeV, \quad m'_{5/3} = 380\,GeV, \quad m'_{2/3} = 390\,GeV,$$

we obtain from (4) - (6) the contributions

$$S^{(LQ)} = -0.05, \quad T^{(LQ)} = -0.04, \quad U^{(LQ)} = -4 \cdot 10^{-4}$$

which agree with (1) at $m_H = 300\,GeV$ with $\chi^2 = 3.5$ (in comparision with $\chi^2 = 5.1$ of the SM).

In a similar way for $\delta = 1$ the scalar leptoquarks with masses

$$m_{2/3} = 300\,GeV, \quad m_{1/3} = 360\,GeV, \quad m'_{5/3} = 360\,GeV, \quad m'_{2/3} = 390\,GeV,$$

give according to (4) - (6) the contributions

$$S^{(LQ)} = -0.03, \quad T^{(LQ)} = -0.16, \quad U^{(LQ)} = -1 \cdot 10^{-3}$$

which agree with the data(1) at $m_H = m_Z$ with $\chi^2 = 2.1$ (in comparision with $\chi^2 = 4.1$ of the SM).

Resuming the result of the work we can conclude that the current experimental data on S, T, U are compatible with the existence the relatively light scalar leptoquars (with the masses of order a few TeV) with favoring the light scalar leptoquarks (with the masses below 1 TeV) which improve the agreement of these data with the theory.

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