Decays of scalar leptoquarks and scalar gluons in the minimal four color symmetry model

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Abstract

The fermionic and weak decays of the scalar leptoquark and gluon doublets are investigated in the minimal four color symmetry model. The fermionic decay modes with production of t- or b- quarks are shown to be the dominant ones. The numerical estimations of the dominant fermionic decay modes and of the weak ones are found and analyzed in dependence on the masses of the decaying particles.

The search for a new physics beyond the Standart Model (SM) is one of the goals of the modern elementary particle physics. One of the possible variant of new physics beyond the SM can be the variant induced by the four color symmetry between quarks and leptons of Pati-Salam type [1]. The four color symmetry in its minimal realization on the gauge group

$$G = SU_V(4) \times SU_L(2) \times U_R(1) \tag{1}$$

in the case of the Higgs mechanism of the quark-lepton mass splitting (a minimal quark-lepton symmetry model, MQLS model[2, 3]) additionally to

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the new gauge particles (vector leptoquarks and Z' boson) predicts also the new particles in the scalar sector – two scalar leptoquarks doublets $S_a^{(\pm)}$, a scalar gluon doublet F_a and an additional colorless doublet Φ'_a, $a = 1, 2$ is the $SU(2)$ index. Due to their Higgs origin the coupling constants of these scalar doublets with fermions occur to be proportional to the ratios m_f/η of the fermion mass to the SM VEV η and hence these coupling constant are known (up to mixing parameters). This gives the possibilities for estimation of the new effects related to these new particles, in particular to estimate their decay widths.

In this talk I would like to present the result of calculations of the decay widths of the scalar leptoquark and scalar gluon doublets and to discuss the dominant decay modes and the corresponding branching ratios in dependence on the masses of these particles.

In the MQLS model the basic left- (L) and right- (R) quarks $Q'^{L,R}_{ia\alpha}$ and leptons $l'^{L,R}_{ia}$ form the fundamental quartets of $SU(4)$ color group, and can be written, in general, as superpositions of the quark and lepton mass eigenstates $Q^{L,R}_{ia\alpha}$ and $l^{L,R}_{ia}$

$$\psi^{L,R}_{ia\alpha} = Q'^{L,R}_{ia\alpha} = \sum_j \left(A^{L,R}_{Q_a}\right)_{ij} Q^{L,R}_{ja\alpha},$$
$$\psi^{L,R}_{ia4} = l'^{L,R}_{ia} = \sum_j \left(A^{L,R}_{l_a}\right)_{ij} l^{L,R}_{ja}, \qquad (2)$$

where i=1,2,3 are the generation indices, $a = 1, 2$ are the $SU_L(2)$ indices and $A = \alpha, 4$ – $SU_V(4)$ indices, $\alpha = 1, 2, 3$ are the $SU_c(3)$ color indices. The unitary matrices $A^{L,R}_{Q_a}$ and $A^{L,R}_{l_a}$ describe the fermion mixing and diagonalize the mass matrices of quarks and leptons. The combinations of these matrices give the Cabibbo-Kobayashi-Maskawa matrix $C_Q = (A^L_{Q_1})^+ A^L_{Q_2}$, the analogous matrix in the lepton sector $C_l = (A^L_{l_1})^+ A^L_{l_2}$ (not diagonal, as it is evident from neutrino oscillation) and unitary mixing matrices $K^{L,R}_a = (A^{L,R}_{Q_a})^+ A^{L,R}_{l_a}$ which are defined by the possible distinctions between the quarks and leptons mixing matrices $A^{L,R}_{Q_a}$ and $A^{L,R}_{l_a}$.

In gauge sector the model predicts new particle – two vector leptoquarks $V^{\pm}_{\alpha\mu} (\alpha = 1, 2, 3)$ and an additional neutral Z' boson. The Higgs mechanism of the quark-lepton mass splitting needs, in general, two scalar multiplets $\Phi^{(2)}$ and $\Phi^{(3)}$ (with VEV η_2 and η_3) transforming according to the representations (1.2.1) and (15.2.1) of the group (1).

The representation (15.2.1) contains 15 $SU_L(2)$ doublets:

$$(15.2.1): \qquad \begin{pmatrix} S^{(+)}_{1\alpha} \\ S^{(+)}_{2\alpha} \end{pmatrix}; \begin{pmatrix} S^{(-)}_{1\alpha} \\ S^{(-)}_{2\alpha} \end{pmatrix}; \begin{pmatrix} F_{1k} \\ F_{2k} \end{pmatrix}; \begin{pmatrix} \Phi^{(3)}_{1,15} \\ \Phi^{(3)}_{1,15} \end{pmatrix}. \qquad (3)$$

Here $S^{(\pm)}_{a\alpha}$ and F_{ak} (k=1,2...8) are the scalar leptoquark and scalar gluons doublets. The scalar doublet $\Phi^{(3)}_{15}$ is mixed with the (1,2,1) doublet $\Phi^{(2)}$ and gives the SM Higgs doublet $\Phi^{(SM)}$ (with SM VEV $\eta = \sqrt{\eta_2^2 + \eta_3^2}$) and an additional Φ' doublet. The scalar doublets (3) have the next electric charges

$$Q_{em}: \qquad \begin{pmatrix} 5/3 \\ 2/3 \end{pmatrix}; \begin{pmatrix} 1/3 \\ -2/3 \end{pmatrix}; \begin{pmatrix} 1 \\ 0 \end{pmatrix}; \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

respectively.

The scalar leptoquarks with electric charge 2/3 are superpositions of three physical scalar leptoquarks S_1, S_3, S_3 and of Goldstone mode S_0

$$S^{(+)}_2 = \sum_m c^{(+)}_m S_m, \ \overset{*}{S}{}^{(-)}_2 = \sum_m c^{(-)}_m S_m.$$

where $c^{(\pm)}_m$ are the elements of the unitary mixing matrix of the scalar leptoquarks with electric charge 2/3.

The interactions of the scalar leptoquarks with fermions can be described by the lagrangians [4],

$$\begin{aligned} L_{ulS^{(+)}_1} &= \bar{u}_{i\alpha}\Big[(h^L_+)_{ij}P_L + (h^R_+)_{ij}P_R\Big] l_j S^{(+)}_{1\alpha} + \text{h.c.}, \\ L_{d\nu S^{(-)}_1} &= \bar{\nu}_j\Big[(h^L_-)_{ij}P_L + (h^R_-)_{ij}P_R\Big] d_{i\alpha} S^{(-)}_{1\alpha} + \text{h.c.}, \\ L_{u\nu S_m} &= \bar{u}_{i\alpha}\Big[(h^L_{1m})_{ij}P_L + (h^R_{1m})_{ij}P_R\Big] \nu_j S_{m\alpha} + \text{h.c.}, \\ L_{dlS_m} &= \bar{d}_{i\alpha}\Big[(h^L_{2m})_{ij}P_L + (h^R_{2m})_{ij}P_R\Big] l_j S_{m\alpha} + \text{h.c.}, \end{aligned}$$

here, $P_{L,R} = (1 \pm \gamma_5)/2$ are the left and right projection operators, $(h^{L,R}_{\pm})_{ij}$ and $(h^{L,R}_{am})_{ij}$ are the coupling constants, i, j are the generation indexes.

As a result of the Higgs fermion mass splitting the MQLS model gives for these coupling constants the expressions

$$
\begin{aligned}
(h^L_+)_{ij} &= \sqrt{3/2}\frac{1}{\eta\sin\beta}\Big[m_{u_i}(K^L_1 C_l)_{ij} - (K^R_1)_{ik} m_{\nu_i}(C_l)_{kj}\Big],\\
(h^R_+)_{ij} &= -\sqrt{3/2}\frac{1}{\eta\sin\beta}\Big[(C_Q)_{ik} m_{d_k}(K^R_2)_{kj} - m_{l_j}(C_Q K^L_2)_{ij}\Big],\\
(h^L_-)_{ij} &= \sqrt{3/2}\frac{1}{\eta\sin\beta}\Big[(\overset{+}{K}{}^R_1)_{ik} m_{u_i}(C_Q)_{kj} - m_{\nu_j}(\overset{+}{K}{}^L_1 C_Q)_{ij}\Big],\\
(h^R_-)_{ij} &= -\sqrt{3/2}\frac{1}{\eta\sin\beta}\Big[(C_l \overset{+}{K}{}^L_2)_{ij} m_{d_j} - (C_l)_{ik} m_{l_k}(\overset{+}{K}{}^R_2)_{kj}\Big],\\
(h^{L,R}_{1m})_{ij} &= -\sqrt{3/2}\frac{1}{\eta\sin\beta}\Big[m_{u_i}(K^{L,R}_1)_{ij} - (K^{R,L}_1)_{ij} m_{\nu_j}\Big] c^{(\pm)}_m,\\
(h^{L,R}_{2m})_{ij} &= -\sqrt{3/2}\frac{1}{\eta\sin\beta}\Big[m_{d_i}(K^{L,R}_2)_{ij} - (K^{R,L}_2)_{ij} m_{l_j}\Big] c^{(\mp)}_m,
\end{aligned}
$$

where $m_{u_i}, m_{d_i}, m_{l_i}, m_{\nu_i}$ are the masses of quarks, of charge leptons and of neutrinos, β is $\Phi^{(2)}_a - \Phi^{(3)}_{15}$ mixing angle in MQLS model, $tg\beta = \eta_3/\eta_2$.

Taking into account that $m_u/\eta, m_d/\eta, m_s/\eta \sim 10^{-5}, m_c/\eta, m_b/\eta \sim 10^{-2}$ but $m_t/\eta \sim 0.7$ we extract from the previous formulas the largest coupling constants in the form

$$
\begin{aligned}
(h^L_+)_{3j} &= \sqrt{\frac{3}{2}}\frac{m_t}{\eta\sin\beta}(K^L_1 C_l)_{3j},\\
(h^L_-)_{i3} &= \sqrt{\frac{3}{2}}\frac{m_t}{\eta\sin\beta}(\overset{+}{K}{}^R_1)_{i3}(C_Q)_{33},\\
(h^{L,R}_{1m})_{3j} &= -\sqrt{\frac{3}{2}}\frac{m_t}{\eta\sin\beta}(K^{L,R}_1)_{3j} m^{(\pm)}_m.
\end{aligned}
$$

As a result among all possible fermionic decay modes scalar leptoquarks

$$S^{(+)}_1 \to u_i l^+_j,\ \ S^{(-)}_1 \to \nu_i \tilde{d}_j,\ \ S_m \to u_i \tilde{\nu}_j,\ \ S_m \to d_i l^+_j$$

there are the next dominant modes

$$S^{(+)}_1 \to t l^+_j,\ \ S^{(-)}_1 \to \nu_i \tilde{b},\ \ S_m \to t\tilde{\nu}_j. \tag{4}$$

The calculation gives the following widths of the dominant modes (4)

$$\Gamma(S^{(+)}_1 \to t l^+_j) = m_{S^{(+)}_1}\frac{3}{32\pi}(\frac{m_t}{\eta})^2 f(\mu_t, \mu_{l_j})\frac{|(K^L_1 C_l)_{3j}|^2}{sin^2\beta}, \tag{5}$$

$$\Gamma(S_1^{(-)} \to \nu_i \tilde{b}) = m_{S_1^{(-)}} \frac{3}{32\pi} (\frac{m_t}{\eta})^2 f(\mu_b, \mu_{\nu_i}) \frac{|(K_1^{R})^{+}_{i3}|^2 |(C_Q)_{33}|^2}{sin^2\beta}, \quad (6)$$

$$\Gamma(S_m \to t \tilde{\nu}_j) = m_{S_m} \frac{3}{32\pi} (\frac{m_t}{\eta})^2 f(\mu_t, \mu_{\nu_i}) \times$$
$$\times \frac{|(K_1^L)_{3j}|^2 |c_m^{(+)}|^2 + |(K_1^R)_{3j}|^2 |c_m^{(-)}|^2}{sin^2\beta}, \quad (7)$$

where $\mu_t = m_t / m_{S_1^{(+)}}$, $\mu_{l_j} = m_{l_j} / m_{S_1^{(+)}}$ and

$$f(\mu_1, \mu_2) = (1 - \mu_1^2 - \mu_2^2) \sqrt{(1 - (\mu_1 + \mu_2)^2)(1 - (\mu_1 - \mu_2)^2)}. \quad (8)$$

Because $m_{l_j}, m_{\nu_i} << m_t$ the function (8) is simplified

$$f(\mu_t, \mu_{l_j}) \approx f(\mu_t, 0) = (1 - m_t^2 / m^2_{S_1^{(+)}})^2.$$

In this case the widths (5)-(7) can be summarized over the generations and using the unitaryty of the matrixes $K_1^{L,R}, C_l$ we obtain the fermion mixing independent expressions for the total decay widths

$$\begin{aligned}
\Gamma(S_1^{(+)} \to t l^+) &= \sum_j \Gamma(S_1^{(+)} \to t l_j^+) \\
&= m_{S_1^{(+)}} \frac{3}{32\pi} (\frac{m_t}{\eta})^2 (1 - \frac{m_t^2}{m^2_{S_1^{(+)}}})^2 \frac{1}{sin^2\beta}, \quad (9) \\
\Gamma(S_1^{(-)} \to \nu \tilde{b}) &= \sum_i \Gamma(S_1^{(-)} \to \nu_i \tilde{b}) \\
&= m_{S_1^{(-)}} \frac{3}{32\pi} (\frac{m_t}{\eta})^2 (1 - \frac{m_b^2}{m^2_{S_1^{(-)}}})^2 \frac{|(C_Q)_{33}|^2}{sin^2\beta}, \quad (10) \\
\Gamma(S_m \to t \tilde{\nu}) &= \sum_j \Gamma(S_m \to t \tilde{\nu}_j^+) \\
&= m_{S_m} \frac{3}{32\pi} (\frac{m_t}{\eta})^2 (1 - \frac{m_t^2}{m^2_{S_m}})^2 \frac{k_m}{sin^2\beta}, \quad (11) \\
k_m &= |c_m^{(+)}|^2 + |c_m^{(-)}|^2,
\end{aligned}$$

The interaction of scalar gluons with quarks can be presented in the form [4]

$$
\begin{aligned}
L_{udF_1} &= \bar{u}_{i\alpha}\Big[(h^L_{F_1})_{ij}P_L + (h^R_{F_1})_{ij}P_R\Big](t_k)_{\alpha\beta}d_{j\beta}F_{1k} + \text{h.c.},\\
L_{uuF_2} &= \bar{u}_{i\alpha}\Big[(h^L_{1F_2})_{ij}P_L\Big](t_k)_{\alpha\beta}u_{j\beta}F_{2k} + \text{h.c.},\\
L_{ddF_2} &= \bar{d}_{i\alpha}\Big[(h^R_{2F_2})_{ij}P_R\Big](t_k)_{\alpha\beta}d_{j\beta}F_{2k} + \text{h.c.}
\end{aligned}
$$

with following coupling constant in MQLS model

$$
\begin{aligned}
(h^L_{F_1})_{ij} &= \sqrt{3}\frac{1}{\eta\sin\beta}\Big[m_{u_i}(C_Q)_{ij} - (K^R_1)_{ik}m_{\nu_k}(\overset{+}{K}{}^L_1 C_l)_{kj}\Big],\\
(h^R_{F_1})_{ij} &= -\sqrt{3}\frac{1}{\eta\sin\beta}\Big[(C_Q)_{ij}m_{d_i} - (C_l K^L_2)_{ik}m_{l_k}(\overset{+}{K}{}^R_2)_{kj}\Big],\\
(h^L_{1F_2})_{ij} &= -\sqrt{3}\frac{1}{\eta\sin\beta}\Big[m_{u_i}(\delta)_{ij} - (K^R_1)_{ik}m_{\nu_k}(\overset{+}{K}{}^L_1)_{kj}\Big],\\
(h^R_{2F_2})_{ij} &= -\sqrt{3}\frac{1}{\eta\sin\beta}\Big[m_{d_i}(\delta)_{ij} - (K^L_1)_{ik}m_{l_k}(\overset{+}{K}{}^R_1)_{kj}\Big].
\end{aligned}
$$

Analogously by to the case of the scalar leptoquarks we neglect in coupling constants all fermion masses except the mass t-quark. So the dominant coupling constants can be written as

$$
\begin{aligned}
(h^L_{F_1})_{33} &= \sqrt{3}\frac{m_t}{\eta\sin\beta}(C_Q)_{33},\\
(h^L_{1F_2})_{33} &= -\sqrt{3}\frac{m_t}{\eta\sin\beta}.
\end{aligned}
$$

As a result we obtain the next dominant fermionic decay modes of the scalar gluons

$$F_1 \to t\bar{b}, \quad F_2 \to t\bar{t}.$$

The calculations give the next widths of these dominant fermionic decay modes

$$\Gamma(F_1 \to t\bar{b}) = m_{F_1}\frac{3}{32\pi}(\frac{m_t}{\eta})^2 f(\mu_t,\mu_b)\frac{|(C_Q)_{33}|}{sin^2\beta}, \qquad (12)$$

$$\Gamma(F_2 \to t\bar{t}) = m_{F_2}\frac{3}{32\pi}(\frac{m_t}{\eta})^2(1 - 2\frac{m_t^2}{\eta^2})^2\sqrt{1 - 4\frac{m_t^2}{m_{F_2}}}\frac{1}{sin^2\beta}. \qquad (13)$$

Table 1: The current experimental limits on the scalar leptoquark masses [5]
.

Genera-tion	Limit on the mass	Decays mode	B	Ref.
I	$m_{LQ} > 242$ GeV	$e\nu jj, eejj, \nu\nu jj$	$B(eq) = 1$	[6]
II	$m_{LQ} > 202$ GeV	$\mu\mu jj$	$B(\mu q) = 1$	[7]
III	$m_{LQ} > 148$ GeV	$\nu\nu bb$	$B(\nu b) = 1$	[8]

We have obtained the numerical estimations for the widths decay using experimental limits on the masses of scalar leptoquarks.

The current experimental limits on the masses of the scalar leptoquarks are shown in table I. In notation of the ref.[5] the scalar leptoquarks of MQLS model are the third generation ones, so from the table I we have the mass limit $m_{S_1^{(-)}} > 148$ GeV only for the scalar leptoquark $S_1^{(-)}$. The analysis of the radiative correction parameters S, T, U favours the scalar leptoquarks and the scalar gluons with masses about 400 GeV or below and about 800 GeV or below respectively [10, 11].

For the further numerical estimations we use the masses of scalar leptoquarks in the range 200-500 GeV and those of the scalar gluons in the range 500-1000 GeV.

The table II shows the typical widths of the scalar leptoquarks and of the scalar gluons. These modes give general contributions in total width decay of scalar leptoquarks and scalar gluons if the mass splitting into doublets scalar leptoquarks and scalar gluons are less than the mass of W boson.

If these mass splitting in the scalar doublets exceeds the W boson mass the weak decay $S \to S'W$ (S and S' are the heaviest and the lightest components of the scalar leptoquark doublet) can be open. The width of this decay can be written in the form

$$\Gamma(S \to S'W) \;=\; \frac{m_S^3 G_F^2}{4\sqrt{2}\pi}\big(1 - \frac{2(m_W^2 + m_{S'}^2)}{m_S^2} + \frac{(m_W^2 - m_{S'}^2)^2}{m_S^4}\big)^{3/2},$$

which agrees with the result of Ref.[12].

Table 2: The the widths of the fermionic decays of the scalar leptoquarks and of the scalar gluons for a different masses of the decaying particles.

$\Gamma(S_1^{(+)} \to t l^+)$	$(0.2 - 1.9 - 5.8)/\sin^2\beta$ GeV	$m_{S_1^{(+)}} = 200 - 300 - 500$ GeV
$\Gamma(S_1^{(-)} \to \nu \tilde{b})$	$(2.3 - 3.0 - 7.5)/\sin^2\beta$ GeV	$m_{S_1^{(-)}} = 150 - 300 - 500$ GeV
$\Gamma(S_m \to t \tilde{\nu})$	$(0.2 - 1.9 - 5.8)/\sin^2\beta$ GeV	$m_{S_m} = 200 - 300 - 500$ GeV
$\Gamma(F_1^{(+)} \to t \tilde{b})$	$(5.8 - 14.0)/\sin^2\beta$ GeV	$m_{F_1} = 500 - 1000$ GeV
$\Gamma(F_2 \to t \tilde{t})$	$(4.1 - 13.3)/\sin^2\beta$ GeV	$m_{F_2} = 500 - 1000$ GeV

Table 3: The widths of the decays $S_1^{(+)} \to t l^+$ and $S_1^{(+)} \to S_2^{(+)} W$ for the different masses $m_{S_1^{(+)}}$ and for the different mass splitting $\Delta m = m_{S_1^{(+)}} - m_{S_2^{(+)}}$.

Widths	$m_{S_1^{(+)}} = 300$ GeV	$m_{S_1^{(+)}} = 500$ GeV	$m_{S_1^{(+)}} = 700$ GeV	Δm
$\Gamma(S_1^{(+)} \to t l^+)$	$1.9/\sin^2\beta$ GeV	$5.8/\sin^2\beta$ GeV	$8.9/\sin^2\beta$ GeV	–
$\Gamma(S_1^{(+)} \to S_2^{(+)} W)$	0.6 GeV	0.8 GeV	0.9 GeV	100 GeV
$\Gamma(S_1^{(+)} \to S_2^{(+)} W)$	4.3 GeV	6.5 GeV	7.3 GeV	150 GeV
$\Gamma(S_1^{(+)} \to S_2^{(+)} W)$	–	16.3 GeV	20.2 GeV	200 GeV

The table III shows the widths of the fermionic and of the weak decays of the scalar leptoquark $S_1^{(+)}$ for a different masses of the up components $S_1^{(+)}$ and for different mass splitting in the doublet. As it can be seen from the table III for the large mass and the mass splitting the weak widths $\Gamma(S_1^{(+)} \to S_2^{(+)} W)$ can be compatible with the fermionic ones. It should be noted also that the fermionic widths have the additional factor $\sin^{-2}\beta$ which can amount to about 25.

The heavy components of the scalar doublets can decay as into fermionic pairs as into light component of the doublet and W-boson whereas the light components of doublets decay predominantly into fermionic pairs with branching ratios of about 1.

In conclusion I resume the results of the work. The decay widths of the scalar leptoquarks and of the scalar gluons are calculated in the minimal four-color quark-lepton symmetry model with the Higgs mechanism of the quark-lepton mass splitting.

It is shown that the dominant modes of the fermionic decays of these scalar particles are the modes with the production of t- or b- quarks.

The typical values of these decay widths are 0.2-7.5 GeV for scalar leptoquarks with the masses 150-500 GeV and 4-14 GeV for scalar gluons with the masses 500-1000 GeV.

The widths of the weak decays $S \to S'W$ of the heaviest component S of the scalar doublet into the lightest one S' are calculated and are shown to be compatible with fermionic widths.

The scalar leptoquarks $S_a^{(\pm)}$ and the scalar gluons F_{ja} discussed above should be searched in their dominant decays $S_1^{(+)} \to t l_j^+$, $S_1^{(-)} \to \nu_i \tilde{b}$, $S_m \to t \tilde{\nu}_j$ and $F_1 \to t\bar{b}$, $F_2 \to t\bar{t}$, which can be interesting for their search at LHC.

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