Mass limits for scalar and gauge leptoquarks from $K^0_L \rightarrow e^\mp \mu^\pm$, $B^0 \rightarrow e^\mp \tau^\pm$ decays

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Abstract

The contributions of scalar and gauge leptoquarks into widths of $K^0_L \rightarrow e^\mp \mu^\pm$, $B^0 \rightarrow e^\mp \tau^\pm$ decays are calculated in the models with the vectorlike and chiral four color symmetry and with the Higgs mechanism of the quark-lepton mass splitting. From the current data on $K^0_L$ and $B^0$ decays the mass limits for scalar and chiral leptoquarks and the updated vector leptoquark mass limits are obtained. It is shown that unlike the gauge leptoquarks the scalar leptoquark mass limits are weak, of order or below their direct mass limits. The search for such scalar leptoquarks at LHC and the further search for leptonic decays $B^0 \rightarrow l^+_i l^-_j$ are of interest.

Keywords: Beyond the SM; four-color symmetry; Pati–Salam; leptoquarks.

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The search for a new physics beyond the Standard Model (SM) is now one of the aims of the high energy physics. Putting LHC into operation will essentially enlarge the possibilities for such search and there is a lot of the variants of new physics which can give new effects at energies of LHC (supersymmetry, left-right symmetry, two Higgs model, etc.).

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 four color symmetry can be unified with the SM by the gauge group

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

where $G_c$ is the group of the four color symmetry. This group can be either the vectorlike group [1–3]

$$G_c = SU_V(4)$$ \hspace{1cm} (2)

or the group of the general chiral four color symmetry

$$G_c = SU_L(4) \times SU_R(4)$$ \hspace{1cm} (3)

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or one of the special groups

\[ G_c = SU_L(4) \times SU_R(3), \quad G_c = SU_L(3) \times SU_R(4) \]  

(4)
of the left (or right) four color symmetry. According to these groups the four color symmetry predicts in the gauge sector either the vector leptoquarks or the left and right leptoquarks or the left (right) gauge leptoquarks respectively. The mass limits for the vector leptoquarks are well known and the most stringent of them are the indirect mass limits resulted from \( K_L^0 \rightarrow e^\pm \mu^\pm \) decay and they are of order of \( 10^3 \) TeV [4–6]. By this reason it is usually thought that the effects of the four color symmetry at the colliders energies are too small to be directly detectable in the collider experiments.

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 were discussed in a number of papers. The experimental lower mass limits for the scalar leptoquarks from their direct search are about 250 GeV or slightly less in dependence on some additional assumptions [8]. As concerns the indirect mass limits for the scalar leptoquarks they 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 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 type (1)–(2) (MQLS model [2, 3, 9]) predicts the \( SU(2)_L \) scalar leptoquark doublets

\[ S^{(\pm)}_{\alpha a} = \left( \begin{array}{c} S^{(\pm)}_{1\alpha a} \\ S^{(\pm)}_{2\alpha a} \end{array} \right) \]  

(5)

with Yukawa coupling constants which occur (due their Higgs origin) to be proportional to the ratios \( m_f/\eta \) of the fermion masses \( m_f \) to the SM VEV \( \eta \). As a result these coupling constants are known (up to mixing parameters) and they are small for the ordinary \( u-, d-, s- \) quarks ( \( m_u/\eta \sim m_d/\eta \sim 10^{-5}, m_s/\eta \sim 10^{-3} \) ) but they are more significant for \( c-, b- \) quarks ( \( m_c/\eta \sim m_b/\eta \sim 10^{-2} \) ) and, especially, for \( t- \) quark ( \( m_t/\eta \sim 0.7 \) ).

The analysis of the contributions of these scalar leptoquark doublets into radiative corrections \( S-, T-, U- \) parameters showed [10, 11] that these scalar leptoquarks can be relatively light, with masses below 1 TeV. Keeping in mind that the most stringent mass limits for the vector leptoquarks are resulted from \( K_L^0 \rightarrow e^\pm \mu^\pm \) decay it is interesting to know what mass limits for the scalar leptoquarks can be extracted from \( K_L^0 \rightarrow e^\pm \mu^\pm \) decay and from other decays of such type.

In this paper we calculate the contributions of the scalar and vector leptoquarks into \( K_L^0 \rightarrow e^\pm \mu^\pm \) and \( B^0 \rightarrow e^\pm \tau^\pm \) decays in frame of MQLS-model based on the vectorlike four color symmetry (1)–(2) and discuss the mass limits resulted from the current data on these decays for the leptoquarks under consideration. We also calculate the contributions into these decays from the chiral gauge leptoquarks induced by the chiral four color symmetry and discuss the corresponding chiral gauge leptoquark mass limits.

In MQLS model the basic left (\( L \)) and right (\( R \)) quarks \( Q_{iaa}^{L,R} \) and leptons \( l_{ia}^{L,R} \) form the fundamental quartets of the group (2) and can be written, in general, as superpositions

\[ Q_{iaa}^{L,R} = \sum_j (A_{Qa}^{L,R})_{ij} Q_{jaa}^{L,R}, \quad l_{ia}^{L,R} = \sum_j (A_{ia}^{L,R})_{ij} l_{ja}^{L,R} \]  

(6)
of the quark and lepton mass eigenstates $Q_{\alpha a i}^{L,R}$, $l_{\alpha ai}^{L,R}$, where $i,j = 1, 2, 3$ are the generation indexes, $a = 1, 2$ and $\alpha = 1, 2, 3$ are the $SU_L(2)$ and $SU_c(3)$ indexes, $Q_{i1} \equiv u_i = (u, c, t)$, $Q_{i2} \equiv d_i = (d, s, b)$ are the up and down quarks, $l_{j1} \equiv \nu_j$ are the mass eigenstates of neutrinos and $l_{j2} \equiv l_j = (e^-, \mu^-, \tau^-)$ are the charged leptons. The unitary matrices $A_Q^{L,R}$ and $A_{l}^{L,R}$ describe the fermion mixing and diagonalize the mass matrices of quarks and leptons.

The Higgs mechanism of the quark-lepton mass splitting needs, in general, two scalar multiplets $\Phi^{(2)}$ and $\Phi^{(3)}$ (with VEV $\eta_2$ and $\eta_3$) transforming according to the representations (1.2.1) and (15.2.1) of the group $[\mathbb{11} -$ $\mathbb{2}]$. The multiplet (15.2.1) contains as a part the scalar leptoquark doublets (5) the down components of which $S_{2a}^{(\pm)}$ have electric charges $\pm 2/3$ and contribute to the leptonic decays of $K^0_L$ and $B^0$ mesons.

In general case the scalar leptoquarks $S_{2a}^{(\pm)}$ and $S_{2a}^{(-)}$ with electric charge 2/3 are mixed and can be written as superpositions

$$S_{2}^{(+)} = \sum_{m=0}^{3} c_{m}^{(+)} S_{m}, \quad S_{2}^{(-)} = \sum_{m=0}^{3} c_{m}^{(-)} S_{m} \quad (7)$$

of three physical scalar leptoquarks $S_{1}, S_{2}, S_{3}$ with electric charge 2/3 and a small admixture of the Goldstone mode $S_{0}$. Here $c_{m}^{(\pm)}$, $m = 0, 1, 2, 3$ are the elements of the unitary scalar leptoquark mixing matrix, $|c_{m}^{(\pm)}|^2 = \frac{1}{3} g_{4} g_{\eta_3}^2 / m_{V}^2 \ll 1$, $g_{4}$ is the $SU_V(4)$ gauge coupling constant, $\eta_3$ is the VEV of the (15,2,1)-multiplet and $m_{V}$ is the vector leptoquark mass.

In particular case of the two leptoquark mixing the superpositions (7) can be approximately written as

$$S_{2}^{(\pm)} = c S_{1} + s S_{2}, \quad S_{2}^{(-)} = -s S_{1} + c S_{2} \quad (8)$$

where $c = \cos\theta$, $s = \sin\theta$, $\theta$ is the scalar leptoquark mixing angle.

The interaction of the vector and scalar leptoquarks with down fermions can be described by the lagrangians

$$L_{Vdi} = \frac{g_4}{\sqrt{2}} (\bar{d}_{pi} [K_{p1i}^{L} \gamma^\mu P_L + (K_{2i}^{R})_{\mu} \gamma^\mu P_R] l_i)V_{\alpha\mu} + h.c. \quad (9)$$

$$L_{Sdi} = (\bar{d}_{pi} (h_{m}^{L})_{pi} P_L + (h_{m}^{R})_{pi} P_R l_i) S_{\alpha \mu} + h.c. \quad (10)$$

where $g_4 = g_m(M_c)$ is the $SU_V(4)$ gauge coupling constant related to the strong coupling constant at the mass scale $M_c$ of the $SU_V(4)$ symmetry breaking and $(h_{m}^{L,R})_{pi}$ are Yukawa coupling constants, $p, i = 1, 2, 3,...$ are the quark and lepton generation indexes, the index $m$ numerates the scalar leptoquarks, $\alpha = 1, 2, 3$ is the $SU(3)$ color index and $P_{L,R} = (1 \pm \gamma_5)/2$ are the left and right operators of fermions. The unitary matrices $K_{a}^{L,R} = (A_{Q_a}^{L,R})^{\pm} A_{l_a}^{L,R}$, $a = 1, 2$ describe the (down for $a = 2$) fermion mixing in the leptoquark currents and in general case they can be nondiagonal. These four matrices are specific for the model with the four color quark-lepton symmetry. Note that although the group (2) has the vector form the interaction (9) in general case is not purely vectorlike because of the possible difference of the mixing matrices in (9) for the left and for the right quarks and leptons. The particular case of the pure vector interaction in (9) with $K_{2}^{L} = K_{2}^{R}$ has been considered in [5, 6].
The Higgs mechanism of the quark lepton mass splitting of MQLS-model gives for Yukawa coupling constants the expressions

\[ (h^L_R)_{pi} = h^L_R e^{i\pi}, \]

\[ h^L_R = -\sqrt{3/2} \frac{1}{\eta \sin \beta} \left[ m_{d_p} (K^L_R)_{pi} - (K^R_L)_{pi} m_i \right] \]

where \( \eta \) is the SM VEV, \( \beta \) is the two Higgs doublet mixing angle of the model, \( m_{d_p}, m_i \) are the quark and lepton masses and \( e^{i\pi} \) are the scalar leptoquark mixing parameters in (7).

We have calculated the contributions of the scalar and vector leptoquarks into the decays \( K^0_L \rightarrow e^\mp \mu^\pm \) and \( B^0 \rightarrow e^\mp \tau^\pm \) with accounting also the gluonic corrections of one loop approximation. The amplitudes of the decays under considerations in tree approximation are calculated in a standard manner and after Fierz transformations these amplitudes depend on the matrix elements of the pseudoscalar and axial quark currents

\[ \langle 0 | \bar{s} \gamma^\mu \gamma^5 d | K^0(p) \rangle = i f_{K^0} p^\mu, \quad \langle 0 | \bar{s} \gamma^5 d | K^0(p) \rangle = -i \bar{m}_{K^0} f_{K^0}, \]

\[ \langle 0 | \bar{b} \gamma^\mu \gamma^5 d | B^0(p) \rangle = i f_{B^0} p^\mu, \quad \langle 0 | \bar{b} \gamma^5 d | B^0(p) \rangle = -i \bar{m}_{B^0} f_{B^0}, \]

where \( p_\mu \) is 4-momentum of the decaying meson and

\[ \bar{m}_{K^0} = m^2_{K^0} / (m_s + m_d), \quad \bar{m}_{B^0} = m^2_{B^0} / (m_b + m_d). \]

The calculations and analysys of the one loop gluonic corrections to the amplitudes of the \( K^0_L \rightarrow e^\pm \mu^\pm \) and \( B^0 \rightarrow e^\pm \tau^\pm \) decays in the case of the scalar leptoquark exchange showed that in the leading logarithm approximation these corrections give rise to the enhancement of the matrix elements of the pseudoscalar quark currents by the factors

\[ R^S_{K^0} = R_{K^0} (\mu_{K^0}, \mu_0^S), \quad R^S_{B^0} = R_{B^0} (\mu_{B^0}, \mu_0^S) \]

depending on mass scale \( \mu_0^S \) at which the Yukawa coupling constants [12] are defined and on mass scales \( \mu_{K^0}, \mu_{B^0} \) at which the decays occur. This dependence can be described as

\[ R_{K^0} (\mu_{K^0}, \mu_0) = R(\mu_{K^0}, m_c; 3) R(m_c, m_b; 4) R(m_b, m_\mu; 5) R(m_\mu, \mu_0; 6), \]

\[ R_{B^0} (\mu_{B^0}, \mu_0) = R(\mu_{B^0}, m_t; 5) R(m_t, \mu_0; 6) \]

with

\[ R(\mu_1, \mu_2; n_f) = [\alpha_{st}(\mu_1)/\alpha_{st}(\mu_2)]^{4/b(n_f)}, \]

where \( \alpha_{st}(\mu) \) is the strong coupling constant at mass scale \( \mu \), \( b(n_f) = 11 - (2/3)n_f \), \( n_f \) is a number of the active quark flavors.

We will consider below the sums of the widths of the charge conjugated decay modes with denoting these sums as

\[ \Gamma(K^0_L \rightarrow e \mu) \equiv \Gamma(K^0_L \rightarrow e^- \mu^+) + \Gamma(K^0_L \rightarrow e^+ \mu^-) = 2\Gamma(K^0_L \rightarrow e^- \mu^+), \]

\[ \Gamma(B^0 \rightarrow e \tau) \equiv \Gamma(B^0 \rightarrow e^- \tau^+) + \Gamma(B^0 \rightarrow e^+ \tau^-) = 2\Gamma(B^0 \rightarrow e^- \tau^+). \]
With omitting the details of calculations the final expressions for the widths of the 
$K^0_L \rightarrow e\mu, B^0 \rightarrow e\tau$ decays induced by the scalar leptoquarks $S_1, S_2$ with mixing (8) and 
with account the one loop gluonic corrections for the case of zero fermion mixing 
$K^0_L = K^R_L = I$ (20) 
can be presented in the form 
$$
\Gamma_S(K^0_L \rightarrow e\mu) = \frac{m_{K^0} f_{K^0}^2 h_d^2 h_s^2}{256\pi} \left(1 - \frac{m^2_{\mu}}{m^2_{K^0}}\right)^2 \times \left\{ m_{\mu} \langle \frac{1}{m_S^2} \rangle^L - R^S_{K^0} \bar{m}_{K^0} c_s \left(\frac{1}{m_{S_1}^2} - \frac{1}{m_{S_2}^2}\right) + L \leftrightarrow R \right\}, 
$$
(21) 
$$
\Gamma_S(B^0 \rightarrow e\tau) = \frac{m_{B^0} f_{B^0}^2 h_d^2 h_s^2}{128\pi} \left(1 - \frac{m^2_{\tau}}{m^2_{B^0}}\right)^2 \times \left\{ m_{\tau} \langle \frac{1}{m_S^2} \rangle^L - R^S_{B^0} \bar{m}_{B^0} c_s \left(\frac{1}{m_{S_1}^2} - \frac{1}{m_{S_2}^2}\right) + L \leftrightarrow R \right\}, 
$$
(22) 
where 
$$
h_p = \sqrt{3}/2 \frac{1}{\eta \sin \beta} (m_{d_p} - m_{u_p}), 
$$
(23) 
$$
\langle \frac{1}{m_S^2} \rangle^L = \frac{s^2}{m_{S_1}^2} + \frac{c^2}{m_{S_2}^2}, \quad \langle \frac{1}{m_S^2} \rangle^R = \frac{c^2}{m_{S_1}^2} + \frac{s^2}{m_{S_2}^2} 
$$
(24) 
and the relations $K^0 = (\tilde{s}d), \tilde{K}^0 = (\tilde{d}s), K^0_L = ((\tilde{s}d) + (\tilde{d}s))/\sqrt{2}, B^0 = (\tilde{b}d)$ have been 
taken into account.

The widths of the decays 
$$
K^0_L \rightarrow l^+_i l^-_j 
$$
(25) 
with $i, j = 1, 2, l^\pm_i = e^\pm, \mu^\pm$ induced by the vector leptoquarks with neglect of electron 
and muon masses ($m_e, m_\mu \ll R^V_{K^0} \bar{m}_{K^0}$) in the case of the general fermion mixing can be 
written as 
$$
\Gamma_V(K^0_L \rightarrow l^+_i l^-_j) = \frac{m_{K^0} \pi \alpha_s^2 f_{K^0}^2 \bar{m}_{K^0}^2 (R^V_{K^0})^2}{4m^4_V} \chi^2_{ij}, 
$$
(26) 
Here the factor $R^V_{K^0} = R_{K^0}($$\mu_{K^0}, M_c)$ accounts the gluonic corrections to the pseudoscalar 
quark current and is defined by equation (17) with mass scale $M_c$ of the four color symmetry breaking and the factors 
$$
\chi_{ij} = \sqrt{(|\chi^{L,R}_{ij}|^2 + |\chi^{R,L}_{ij}|^2)/2} 
$$
(27) 
with 
$$
\chi^{L,R}_{ij} = (K^{L,R}_2)_{2i} (K^{R,L}_2)^*_{1j} + (K^{L,R}_2)_{1i} (K^{R,L}_2)^*_{2j} 
$$
(28) 
account the fermion mixing of the general form.
In particular, for the total width of the $K_L^0 \to e^+ \mu^\pm$ decays we have

$$\Gamma_V(K_L^0 \to e\mu) = \frac{m_{K^0} f_{K^0}^2 m_{\mu}^2 (R_{K^0}^V)^2 \kappa_{21}^2}{2m_{V}^4}$$  \quad (29)$$

where the mixing factor $\kappa_{21}$ depends on the fermion mixing via (27), (28) and can be varied in the region $0 \leq \kappa_{21} \leq 1$. In particular case of $K_L^0 = K^0_2$ the factor $\kappa_{21}$ reproduces the corresponding factor of refs. [5,6]. In the case (20) of zero fermion mixing $\kappa_{21} = 1$ and the decays $K_L^0 \to e^+ \mu^\pm$ are the only possible decays of type (25) with the total width (29) at $\kappa_{21} = 1$. In this case the width (29) coincides with that of ref. [4].

The total width of the $B^0 \to e^+ \tau^\pm$ decays induced by the vector leptoquarks with neglect of electron mass ($m_e \ll R_{B^0}^V \bar{m}_B$, $m_\tau$) in the case of zero fermion mixing (20) can be written as

$$\Gamma_V(B^0 \to e\tau) = \frac{m_{B^0} f_{B^0}^2 m_\mu^2 (R_{B^0}^V)^2 \kappa_{21}^2}{m_{V}^4} (R_{B^0}^V \bar{m}_B - m_\tau/2)^2 \left(1 - \frac{m_\mu^2}{m_{B^0}^2}\right)^2$$  \quad (30)$$

where the factor $R_{B^0}^V = R_{B^0}^V(\mu_{B^0}, m_e)$ accounts the gluonic corrections.

For comparison with the case of the vector leptoquarks $V$ we have also calculated the widths of $K_L^0 \to e^+ \mu^\pm$ and $B^0 \to e^+ \tau^\pm$ decays induced by the left ($V_L$) and right ($V_R$) chiral gauge leptoquarks.

The interaction of the chiral gauge leptoquarks with fermions can be written as

$$L_{V_{dl}} = \frac{g_4^L}{\sqrt{2}} \bar{d}_{\alpha}(K_2^L)_{\mu \gamma \alpha \mu}(L_i) V_{\alpha \mu}^L + \frac{g_4^R}{\sqrt{2}} \bar{d}_{\alpha}(K_2^R)_{\mu \gamma \alpha \mu}(L_i)V_{\alpha \mu}^R + h.c.,$$  \quad (31)$$

where $g_4^L$, $g_4^R$ are the gauge coupling constants of the group (3) or (4) which are related to strong coupling constant by the equation

$$g_4^L g_4^R \sqrt{(g_4^L)^2 + (g_4^R)^2} = g_{st}.$$  \quad (32)$$

The resulted total widths of the $K_L^0 \to e\mu$, $B^0 \to e\tau$ decays with account of the contributions of the chiral gauge leptoquarks $V_L, V_R$ with neglecting the electron mass can be written as

$$\Gamma_{V_{LR}}(K_L^0 \to e\mu) = \frac{m_{K^0} f_{K^0}^2 m_{\mu}^2}{64\pi} \left(1 - \frac{m_\mu^2}{m_{K^0}^2}\right)^2 \left[\frac{(g_4)^4}{4m_{V_L}^4} |\kappa_{21}^{LR}|^2 + L \leftrightarrow R\right],$$  \quad (33)$$

$$\Gamma_{V_{LR}}(B^0 \to e\tau) = \frac{m_{B^0} f_{B^0}^2 m_\tau^2}{32\pi} \left(1 - \frac{m_\tau^2}{m_{B^0}^2}\right)^2 \left[\frac{(g_4)^4}{4m_{V_L}^4} |k_{31}^{LR}|^2 + L \leftrightarrow R\right]$$  \quad (34)$$

where the parameters

$$\kappa_{ij}^{LR} = (K_2^{LR})_{2i}^* (K_2^{LR})_{1j} + (K_2^{LR})_{1i}^* (K_2^{LR})_{2j},$$  \quad (35)$$

$$k_{ij}^{LR} = (K_2^{LR})_{3i}^* (K_2^{LR})_{1j}$$  \quad (36)$$

account the effects of the general fermion mixing. The widths (33), (34) depend on the matrix elements of the axial currents in (13), (14) and as it has been shown by the
corresponding analyses the gluonic corrections of the leading logarithm approximation in this case are absent.

We have numerically analysed the widths (21), (22), (29), (30) and (33), (34) in dependence on the leptoquark masses. The Yukawa coupling constants (12) are defined by the quark masses at the mass scale $\mu_0^S = \eta$ of order of the mass scale of the SM symmetry breaking, $\eta = 250 \text{GeV}$ is the SM VEV. The gauge coupling constants are related to $g_{st}(M_\ell)$ at $\mu_0^V = M_\ell = 1000 \text{TeV}$, in the case of chiral gauge leptoquarks we assume also that $g_{41} = g_{41}^R(= \sqrt{2}g_{st})$. The mass scales of the decaying particles are chosen at $\mu_{K^0} = 1 \text{GeV}$ and $\mu_{B^0} = m_{B^0}$ for $K^0_L$ and $B^0$ decays respectively and these mass scales are also used for defining the quark masses in (13), (14), (15). With implying the isotopic symmetry we use the value of the form factor $\kappa = \sqrt{2}$ also that $g_{41} = g_{41}^R(= \sqrt{2}g_{st})$. The mass scales of the decaying particles are chosen at $\mu_{K^0} = 1 \text{GeV}$ and $\mu_{B^0} = m_{B^0}$ for $K^0_L$ and $B^0$ decays respectively and these mass scales are also used for defining the quark masses in (13), (14), (15). With implying the isotopic symmetry we use the value of the form factor $\kappa = \sqrt{2}$

$$B_{\tau}(K^0_L \to e\mu) < 4.7 \cdot 10^{-12}. \tag{37}$$

The first two curves correspond to the case of the chiral scalar leptoquark mass states for $m_S = m_{SL} \ll m_{SR}$ (curve 1) and for $m_S = m_{SL} = m_{SR}$ (curve 2). The next two curves correspond to the case of the leptoquark mass states of the scalar type $m_S = m_{SS} \ll m_{SP}$ (curve 3) and of the pseudoscalar one $m_S = m_{SP} \ll m_{SS}$ (curve 4). As seen in all the cases the lower mass limits for the scalar leptoquarks are small, of order or below the mass limits from the direct search for scalar leptoquarks.

More exactly, from (21) and (37) we obtain the next scalar leptoquark mass limits

$$m_{SL}, m_{SR} > 15/\sin \beta \text{ GeV}, \tag{38}$$

$$m_{SS}, m_{SP} > 60/\sin \beta \text{ GeV}. \tag{39}$$

For a validity of a perturbation theory the Yukawa coupling constants including those for $t$-quark should be sufficiently small, which implies that $0.2 \leq \sin \beta \leq 1$. So, the lower mass limits (38) for chiral scalar leptoquarks are below the mass limits from the direct search for scalar leptoquarks and those (39) for the scalar leptoquarks of scalar or pseudoscalar types can be of order or below their direct mass limits.

Fig.2 shows the branching ratios of $K^0_L \to e\mu$ decay as a function of the ratios $m_V/\sqrt{|\omega_{21}|}$, $m_{VL}/\sqrt{|\omega_{21}|}$ of the masses $m_V$, $m_{VL}$ of the vector and chiral gauge leptoquarks to the corresponding fermion mixing parameters. The branching ratio of $K^0_L \to e\mu$ decay as a function of the ratio $m_V/\sqrt{|\omega_{21}|}$ is shown for the cases with account of gluonic corrections (curve 1) and (for comparison) with neglecting them (dashed line). The curve 2 shows the branching ratio of $K^0_L \to e\mu$ decay in dependence on the ratio $m_{VL}/\sqrt{|\omega_{21}|}$ with assuming for definiteness that $m_{VL} \ll m_{VR}$. As seen, in the case of zero fermion mixing ($\omega_{21} = \omega_{21}^L = 1$) the mass limits for the gauge leptoquarks are essentially more stringent than those for the scalar leptoquarks.

Using (29), (33) and (37) we obtain from $K^0_L \to e^\mp \mu^\pm$ decays the next gauge leptoquark mass limits

$$m_V > \sqrt{|\omega_{21}|} \quad 2000 \text{ TeV}, \tag{40}$$

$$m_{VL} > \sqrt{|\omega_{21}^L|} \quad 260 \text{ TeV}. \tag{41}$$
for the vector and chiral (with assuming $m_{V_L} \ll m_{V_R}$) gauge leptoquarks. The mass limit (40) for the vector leptoquarks copresponsible to the current date (37) and it is more stringent than the known one [5, 6, 8] whereas (41) is the new mass limit for the chiral gauge leptoquarks.

It interesting to note that the simultaneous account of the gauge and scalar leptoquark contributions into decays under consideration can weaken the leptoquark mass limits due the possible destructive interference of these contributions. For example such destructive interference takes place between the contributions of the vector leptoquarks $V$ and of the scalar leptoquarks $S$ of the scalar type. For $m_S$ from (39) this interference reduces the mass limit for vector leptoquarks from (40) to $m_V > \sqrt{k_{31}^2} 1400$ TeV.

The current experimental limit on the total branching ratio of $B^0 \to e^\mp \tau^\pm$ decays [8] gives the relatively weak limits on the leptoquark masses.

The lower mass limits from $B^0 \to e^\mp \tau^\pm$ decays for the scalar leptoquarks resulted from (22), (12) are only of order of a few GeV, i.e. they are essentially weaker than those (38), (39) from $K^0_L \to e^\mp \mu^\pm$ decays.

Using (30), (34) and (42) we have obtained from $B^0 \to e^\mp \tau^\pm$ decays the next mass limits for the gauge leptoquarks

$$m_V > 9.3 \text{ TeV},$$
$$m_{V_L} > \sqrt{|k_{31}^L|} 2.8 \text{ TeV}.$$  

The mass limit (43) correspond to the case (20) and can be lowered by the fermion mixing. The mass limits (43), (44) are weaker than those (40), (41) from $K^0_L \to e^\mp \mu^\pm$ decays nevertheless they are of interest as the new independent ones.

It is worth to note that unlike the $K^0_L$-decays (25) in the case of $B^0$-meson all the decays

$$B^0 \to l^+_i l^-_j$$

with $i, j = 1, 2, 3, l^\pm_i = e^\pm, \mu^\pm, \tau^\pm$ are allowed. The search for the decays (45) and the measurements of their branching ratios will give the possibility to set the leptoquark mass limits with account of the fermion mixing of the general form and are of interest.

In conclusion we resume the results of the work. The contributions of the scalar and gauge leptoquarks into widths of the $K^0_L \to e^\mp \mu^\pm$, $B^0 \to e^\mp \tau^\pm$ decays are calculated in the models with the vectorlike and chiral four color symmetry and with the Higgs mechanism of the quark-lepton mass splitting. From the current data on leptonic $K^0_L$ decays the mass limits (38), (39), (41) for scalar and chiral leptoquarks as well as the updated mass limit (40) for vector leptoquarks are obtained. The gauge leptoquark mass limits (43), (44) from the current data on $B^0 \to e^\mp \tau^\pm$ decays are also obtained, which occur to be essentially weaker than those from $K^0_L \to e^\mp \mu^\pm$ decays. It is shown that in all the cases considered the scalar leptoquark mass limits (unlike the gauge leptoquark ones) are weak, of order or below their direct mass limits. The search for such scalar leptoquarks at LHC and the further search for the leptonic decays $B^0 \to l^+_i l^-_j$ are of interest.

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Figure captions

Fig. 1. Branching ratio of $K_L^0 \to e\mu$ decay in dependence on $m_S \sin \beta$ for
1) $m_S = m_{SL} \ll m_{SR}$, 2) $m_S = m_{SL} = m_{SR}$, 3) $m_S = m_{SS} \ll m_{SP}$,
4) $m_S = m_{SP} \ll m_{SS}$.

Fig. 2. Branching ratio of $K_L^0 \to e\mu$ decay in dependence on the ratio $m_V/\sqrt{\kappa_{21}}$ of the vector leptoquark mass to the fermion mixing parameter $\sqrt{\kappa_{21}}$ with account of gluonic corrections (curve 1) and with neglecting them (dashed line) and on the ratio $m_{VL}/\sqrt{|\kappa_{21}'|}$ of the left chiral leptoquark mass to the fermion mixing parameter $\sqrt{|\kappa_{21}'|}$ (curve 2).
Fig. 2