Scalar leptoquark contributions into the magnetic moment of neutrino in the minimal model with the four-color symmetry

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Abstract

The limits on the scalar leptoquark masses from the astrophysical data on the magnetic moment of neutrino in the minimal model with four-color symmetry are calculated. It is shown that the magnetic moment of neutrino data admit area of mixing parameters within masses of the scalar leptoquark below 1 TeV down to experimental limits from direct production. In the case of degenerate masses of the scalar leptoquark S_m (Q=2/3) independent on the mixing parameter model limit $m_{S_m} > 330$ GeV is obtained. The comparisons with the prediction of other leptoquark models are discussed.

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. The minimal realization this symmetry MQLS model [1] is based on the group

$$G = SU_V(4) \times SU_L(2) \times U_R(1).$$

This symmetry predicts the existence of scalar leptoquark doublets [2]. The scalar leptoquarks that arise in the MQLS model may be light - that is their masses may be about 1 TeV and lower (as follows from an analysis of their contributions to S, T and U parameter [3] and to muon anomalous magnetic moment [4]).

In this talk, I examine the contribution to the neutrino magnetic moment (NMM) from scalar leptoquarks appearing in the MQLS model.

In the MQLS model the basic left- (L) and right- (R) handed 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 $l^{L,R}_{ia}$

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

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. This matrices combiners $C_Q = (A^L_{Q_1})^+ A^L_{Q_2}$ the Cabibbo-Kobayashi-Maskawa matrix, which is know to be due to the distinction between the mixing matrices $A^L_{Q_1}$ and $A^L_{Q_2}$ for up and down left-handed quarks, $C_l = (A^L_{l_1})^+ A^L_{l_2}$ the matrix that is analog its in the lepton sector and is not diagonal, this evident from neutrino oscillation, which is due to the possible distinction between the mixing matrices $A^L_{l_1}$ and $A^L_{l_2}$ and $K^{L,R}_a = (A^{L,R}_{Q_a})^+ A^{L,R}_{l_a}$ unitary matrices additional fermion mixing in

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model (that are due to the possible distinctions between the quarks and leptons mixing matrices $A^{L,R}_{Q_a}$ and $A^{L,R}_{l_a}$).

In gauge sector model predicted of two vector leptoquarks $V^{\pm}_{\alpha\mu}(\alpha = 1, 2, 3)$ and of additional neutral Z' boson.

The scalar sector of the model, contains four multiplets, which transformed according to $(4, 1, 1)$, $(1, 2, 1)$, $(15, 2, 1)$, $(15, 1, 0)$ representations with respectively VEV η_1, η_2, η_3 and η_4. The scalar fields, that have $SU_L(2)-$ doublet origin interact with the fermions.

The MQLS model is based on the Higgs mechanism of splitting of the quarks and leptons masses. In this approach, the SM Higgs doublet $\Phi^{(SM)}$ appearing to be superposition of the doublet from the representation (1.2.1) and colorless doublet from the representation (15,2,1). The vacuum expectation value in the Standard Model is $\eta = \sqrt{\eta_2^2 + \eta_3^2}$ and β is mixing angel $\tan\beta = \eta_3/\eta_2$.

The representation (15,2,1) contains, in particular, two doublets SLQs $S^{(\pm)}_a$

$$\Phi^{(3)} \quad (15.2.1) \quad \begin{pmatrix} S^{(+)}_{1\alpha} \\ S^{(+)}_{2\alpha} \end{pmatrix}; \begin{pmatrix} S^{(-)}_{1\alpha} \\ S^{(-)}_{2\alpha} \end{pmatrix},$$

with electric charges of the component scalar doublets.

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

The scalar leptoquarks with electric charge 2/3 are superpositions three physical scalar leptoquarks S_1, S_2, S_3 and Goldstone mode S_0,

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

where $C^{(\pm)}_m$ $m = 0, 1, 2, 3$ are the elements of the complex unitary (4×4) scalar leptoquark of electric charge 2/3 mixing matrix.

The physical SLQs are $S^{(+)}_{1\alpha}, S^{(-)}_{1\alpha}$ with $Q = 5/3$ and $Q = 1/3$ and $S_{m\alpha}$, $m = 1, 2, 3$ with $Q = 2/3$.

The lagrangian interaction scalar leptoquarks with neutrino can be written in the following form,

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

here, $P_{L,R} = (1 \pm \gamma_5)/2$ are projection operators and $(h^{L,R})_{ij}$ are generation-matrix Yukawa coupling in the MQLS model.

The expression for coupling constant because of the Higgs origin are proportional to the ratios of the fermion masses to the VEV in SM. With the exception of $m_t/\eta \sim 0.7$, these ratios are small: $m_u/\eta, m_d/\eta \sim 10^{-5}$, $m_s/\eta \sim 10^{-3}$ and $m_c/\eta, m_b/\eta \sim 10^{-2}$. For the numerical estimations we neglected in coupling constants all fermion masses, except the t- and b-quark masses.

The dominant contributions to the coupling constants can be represented as

$$\begin{aligned} (h^L_-)_{i3} &= \sqrt{\frac{3}{2}} \frac{m_t}{\eta \sin\beta} (\overset{+}{K}{}^R_1)_{i3} (C_Q)_{33}, \\ (h^R_-)_{i3} &= -\sqrt{\frac{3}{2}} \frac{m_b}{\eta \sin\beta} (C_l \overset{+}{K}{}^L_2)_{i3}, \\ (h^{L,R}_{1m})_{3j} &= -\sqrt{\frac{3}{2}} \frac{m_t}{\eta \sin\beta} (K^{L,R}_1)_{3j} C^{(\pm)}_m, \end{aligned} \tag{1}$$

It is necessary to note than, the SLQs in the MQLS model is not chiral and much like the LQs 3rd generation.

The contribution of scalar leptoquarks to the Neutrino Magnetic Moment(NMM) is described by the two diagrams in figure 1. This diagrams describe the amplitude, where $F(p^2)$,

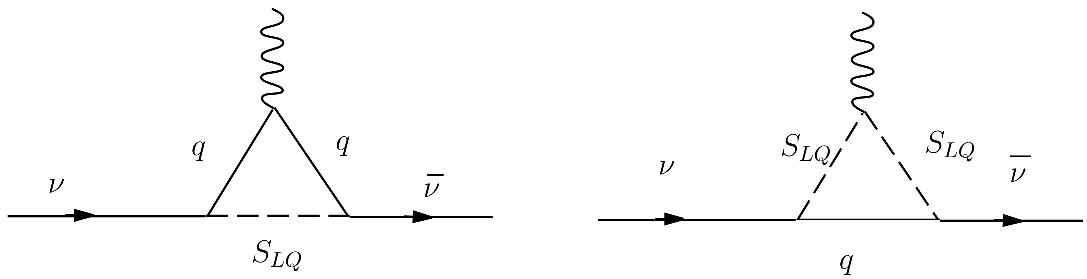

Figure 1: Diagrams representing the contribution of scalar leptoquarks to the Neutrino Magnetic Moment: $q = u_i(d_i)$ is the up(down) quark of the ith generation and $S_{LQ} = S_m(S_1^{(-)})$ is the SLQ corresponding to the above quarks.

$g(p^2)$ are electric and magnetic form factors, $A_\mu(p)$ is electromagnetic field.

$$M = e\bar{\nu}(F(p^2)\gamma^\mu - g(p^2)\frac{\sigma^{\mu\rho}}{2m_\nu}p^\rho)\nu A_\mu(p),$$

The neutrino magnetic moment is calculated as the magnetic form factor $g(0)$.

$$\mu_\nu \equiv g(0)$$

In general, the total one-loop contribution from this diagrams can be written as

$$\begin{aligned} \mu_{\nu_i} &= -\frac{N_c m_e}{16\pi^2 m_{LQ}^2}\mu_B\Bigg[m_{\nu_i}\Big(Q_j F_5(x_j) - Q_s F_2(x_j)\Big)\Big(|(h^L)_{ji}|^2 + |(h^R)_{ji}|^2\Big) \\ &+ m_j\Big(Q_j F_6(x_j) - Q_s F_3(x_j)\Big)\Big(\frac{(\overset{+}{h}^L)_{ij}(h^R)_{ji} + (\overset{+}{h}^R)_{ij}(h^L)_{ji}}{2}\Big)\Bigg], \end{aligned} \qquad (2)$$

where $N_c = 3$ is color factor, Q_j, Q_S are electric charge of q_j-quark and SLQ, μ_B is Bohr magneton, and $x_j = m_j^2/m_{LQ}^2$. The functions $F(x)$ are

$$\begin{aligned} F_2(x) &= \frac{1}{6(1-x)^4}(1 - 6x + 3x^2 + 2x^3 - 6x^2\ln x), \\ F_3(x) &= \frac{1}{(1-x)^3}(1 - x^2 + 2x\ln x), \\ F_5(x) &= \frac{1}{6(1-x)^4}(2 + 3x - 6x^2 + x^3 - 6x\ln x), \\ F_6(x) &= \frac{1}{(1-x)^3}(-3 + 4x - x^2 - 2\ln x). \end{aligned}$$

As can be seen from equation (2) the first term is proportional to the neutrino mass, which the second term is proportional to the quark mass. Therefore, we can retain only the second term in our numerical calculations.

General Contribution of SLQ with Q=2/3

Substituting the numerical values into expressions (2), we obtain

$$\begin{aligned}
\mu_{\nu_i} &= -4 \cdot 10^{-8} \mu_B \sum_{m=1}^{3} x_m \Big(Q_t F_6(x_m) - Q_s F_3(x_m) \Big) k_{mi}, && (3)\\
k_{mi} &= \frac{\overset{+}{(K_1^R)}_{i3}(K_1^L)_{3i} \quad \overset{+}{C}{}_m^{(+)} C_m^{(-)} + \overset{+}{(K_1^L)}_{i3}(K_1^R)_{3i} \quad \overset{+}{C}{}_m^{(-)} C_m^{(+)}}{2 \sin^2 \beta}, \\
x_m &= \frac{m_t^2}{m_{S_m}^2}, \quad \sin\beta > 0.2.
\end{aligned}$$

where k_{mi} is the mixing parameter in the model. The mixing parameter k_{mi} includes unknown matrix elements $(K_1^{L,R})_{3i}$, unknown elements of the leptoquark mixing matrix $C_m^{(\pm)}$ and an unknown mixing angle β ($\sin\beta > 0.2$ from the requirement that perturbation theory be applicable to the t quark coupling constant). So that k_{mi} may be small(about $10^{-3} - 10^{-2}$).

For comparison we have the restriction on the NMM from astrophysical data [5]

$$\mu_\nu < 3 \times 10^{-12} \mu_B \tag{4}$$

Case 1: We assume that the masses of the SLQ S_m are degenerate (this is not necessarily in general). From the unitary condition of leptoquark mixing matrix we have

$$\sum_{m=1}^{3} \overset{+}{C}{}_m^{(\pm)} C_m^{(\mp)} = -|C_0^{(\pm)}|^2 \sim -\frac{\eta^2}{m_V^2} \sin^2\beta < 2 \cdot 10^{-4}.$$

where η is VEV SM, $m_V > 18\ TeV$ is vector leptoquark mass [6](for the four-color theory of Pati-Salam type). We have following form expression

$$\mu_{\nu_i} = 7.6 \cdot 10^{-12} \mu_B x \Big(Q_t F_6(x) - Q_s F_3(x) \Big) k_i,$$

in this case k_i mixing parameter in model have more simple form

$$k_i = \frac{1}{2} \Big(\overset{+}{(K_1^R)}_{i3}(K_1^L)_{3i} + \overset{+}{(K_1^L)}_{i3}(K_1^R)_{3i} \Big) \text{ and } x = \frac{m_t^2}{m_{S_m}}.$$

For k_i=0.5(1) we have lower bounds on masses SLQ 120(330) GeV.

In particular case, $K^L = K^R = K$ (The sum on neutrino generation for mixing parameter give one $\sum k_i = 1$) independent on K matrix and β mixing angel bound are 330 GeV.

The constraints on the SLQ mass from the NMM are given in Figure 2. In Fig.2 shows the NMM as function of the mass of the SLQ, at various values of the parameter k_i. It can be seen for $k_i < 0.4$ lower bound on mass SLQ of charge 2/3 less than the experimental limit on direct searches $M_{LQ} > 100$ GeV [7] (for 3rd generation).

Case 2: In the case the absence of the SLQ mass degeneracy to make an estimate of the contribution of the lightest SLQ in the NMM. In this case we use general form for the NMM equation (3) only without sum over index m - number SLQ with Q=2/3. We have following expression

$$\mu_{\nu_i} = -4 \cdot 10^{-8} \mu_B x_m \Big(Q_t F_6(x_m) - Q_s F_3(x_m) \Big) k_{mi} \tag{5}$$

The lower limit on the mass a lightest SLQ in the absence of the SLQ mass degeneracy at different value parameter k_{mi} are shown in Table 1 and Figure 3.

As be seen from this figure for parameter $k_{mi} < 10^{-3}$ mass the lightest SLQ can be in order 1 TeV and below.

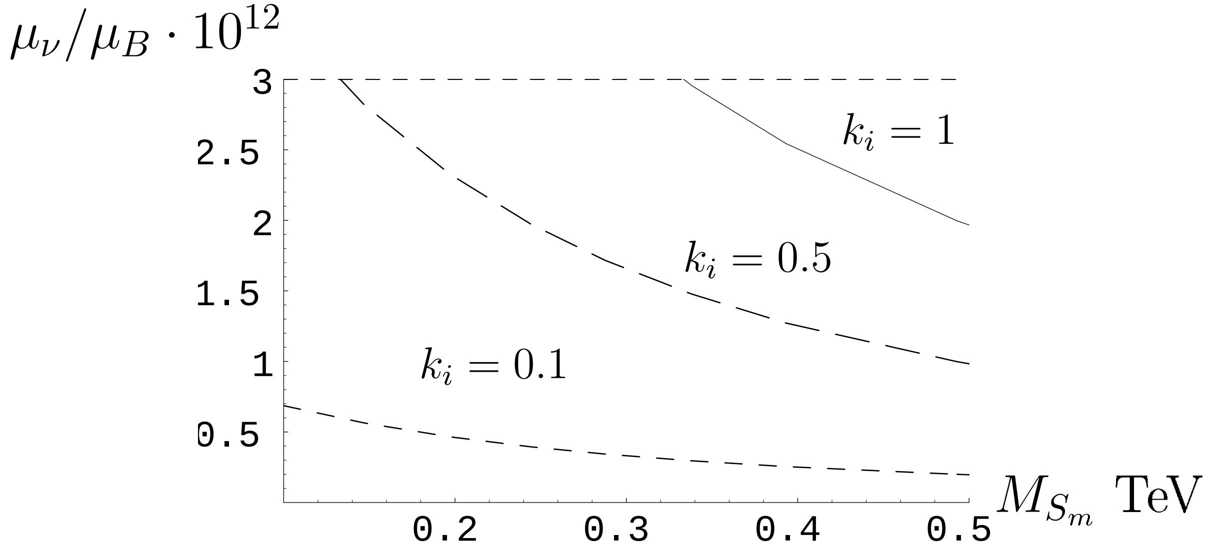

Figure 2: Ratio μ_ν/μ_B as a function of the mass M_{S_m} degenerate SLQ S_m at different value k_i. The horizontal straight line indicate the boundary $\mu_\nu < 3 \times 10^{-12}\mu_B$.

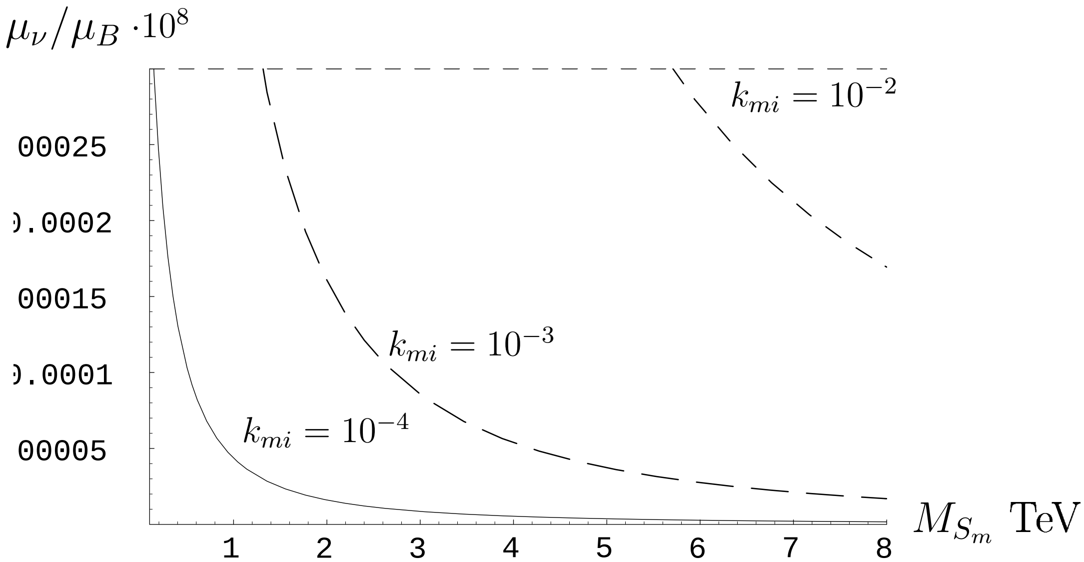

Figure 3: Ratio μ_ν/μ_B as a function of a lightest SLQ mass M_{S_m} in the absence of the SLQ mass degeneracy at different values of k_{mi}. The horizontal straight line indicate the boundary $\mu_\nu < 3 \times 10^{-12}\mu_B$.

Table 1: The lower limit on the mass of a lightest SLQ S_m in the absence of the SLQ mass degeneracy independence on k_{mi}.

$-k_m$	0.1	10^{-2}	10^{-3}	10^{-4}
m_{S_m} TeV	22	4.9	1.3	0.15

Case 3: Other simple variant model if down components scalar doublets are physical particles (only two doublet SLQ in model). In this case lagrangian and coupling constants have simple form

$$L_{t\nu_j S} = \bar{t}_\alpha\Big[-(h_1^L)_{3j}S_2^{(+)}P_L - (h_1^R)_{3j}\overset{*}{S}{}_2^{(-)}P_R\Big]\nu_j + \text{h.c.},$$

$$(h_1^{L,R})_{3j} \approx \sqrt{\frac{3}{2}}\frac{m_t}{\eta\sin\beta}(K_1^{L,R})_{3j}. \tag{6}$$

But in this case the NMM is proportional neutrino mass and it expression for the magnetic moment of the $\tau-$neutrino can be written as

$$\mu_{\nu_\tau} = -1.5\cdot 10^{-19}\mu_B(\frac{m_{\nu_\tau}}{1\text{ eV}})x\Big(Q_jF_5(x) - Q_sF_2(x)\Big)\frac{|(K_1^L)_{33}|^2}{\sin^2\beta}.$$

Therefore masses of the chiral LQs have boundaries from the NMM less than the recent experimental limit on direct searches.

Case 4: Contribution SLQ $S_1^{(-)}$ with Q=1/3 into the magnetic moment of neutrino is suppressed by factor $(m_t/m_b)^2$ compared with one originated by S_m with Q= 2/3 [Case 1]. Using the estimate $x = (m_b/m_{S_1^{(-)}})^2 < 10^{-3}$, at a scalar leptoquark mass 3rd generation about 150 GeV, we obtain

$$\mu_{\nu_i}^{(S_1^{(-)})} < 10^{-14}\mu_B k^{(-)}.$$

The constraint on the $S_1^{(-)}$ SLQ mass from the NMM is lower than the one from direct searches [7]

$$m_{S_1^{(-)}} > 102\ GeV,\ (\text{for} k^{(-)} = 25) \qquad m_{LQ}^{dir} > 148\ GeV.$$

BRW model: For comparison we are studied other model leptoquark - BRW model [8]. In this model SLQs are chiral and their contribution are small [Case 3]. Modified BRW model: an SLQ interaction with a singlet right-handed neutrino is introduced [9].

$$L_{F=0} = (h_{2L}\bar{u}_R l_L i\tau_2 + h_{2R}\bar{q}_L e_R)R_2 + (\tilde{h}_{2L}\bar{d}_R l_L i\tau_2 + \tilde{h}_{2R}\bar{q}_L\nu_R)\tilde{R}_2 + c.c.$$

At this condition SLQ $\tilde{R}_2$ with Q=1/3 and $\tilde{h}_{2L} = \tilde{h}_{2R} = e$ give contribution in the NMM

$$\mu_\nu = 0.3\cdot 10^{-7}\mu_B x(1 + \ln x),$$

and

$$m_{LQ} > 1.5\ TeV.$$

Summary

It is shown that in MQLS model the astrophysical restriction on the neutrino magnetic moment $\mu_\nu < 3\times 10^{-12}\mu_B$ admits an existence of mixing parameters for which the masses of scalar leptoquarks can be below 1 TeV.

In the case of degenerate masses of the scalar leptoquarks S_m ($Q = 2/3$) and for $K^L = K^R = K$, the SLQ mass limit 330 GeV independent on a mixing matrix K and β mixing angle is obtained.

For the chiral SLQs ($Q = 2/3$) and the SLQ $S_1^{(-)}$ ($Q = 1/3$), the NMM gives limits on their masses which are below resent experimental restriction from direct searches.

The mass limit $M_{LQ} > 1.5$ TeV for the SLQ (Q=1/3) in the modified BRW model with $h_L = h_R = e$ is obtained. This limit is stronger than the one $M_{LQ} > 102$ GeV for the same type of SLQ in MQLS model.

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References

[1] A. D. Smirnov, Phys. Lett. B **346**, 297 (1995); Yad. Fiz. **58**, 2252 (1995). (Physics of Atomic Nuclei **58**, (1995).)

[2] A.V. Povarov and A. D. Smirnov, Yad.Fiz. **64**, 78 (2001). (Physics of Atomic Nuclei **64**, No.1, 74 (2001).)

[3] A. D. Smirnov, Phys.Lett.B **431**, 119 (1998); Yad.Fiz **64**, 367 (2001); Phys. Lett. B **513**, 237 (2002); A.V. Povarov and A. D. Smirnov, Yaf.Fiz. **66**, No.12, 2259 (2003).

[4] A.V. Povarov, Yad.Fiz. **69**, No.5, 903 (2006). (Physics of Atomic Nuclei **69**, No.5, 876 (2006).):

[5] G.G.Raffelt, Stars as Laboratories for Fundamental Physics. Chicago. The University of Chicago Press, 1996.

[6] Kuznetsov A.V., Mikheev N.V. Phys.Lett.B **329**, 295 (1994); YaF. **58**, No 12, 2228 (1995).

[7] S.Eidelman et al, PDG. Phys.Lett.B 592, 1 (2004).

[8] W. Buchmüller, R. Rückl and D. Wyler, Phys. Lett. B **191** (1987) 442.

[9] Chun-Khiang Chua and W.-Y.P. Hwang, Phys.Rev.D **60**, 073002 (1999)