Scalar Leptoquark Contributions into $l_i \to l_j\gamma$ Processes

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Plan

1. **Introduction**
2. **Model**
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1. Introduction

Physics Beyond the SM ➞ Four-color symmetry ➞

[J.C. Pati and A.Salam, PRD **10** (1974)]

➞ Minimal Quark-Lepton Symmetry Model ➞

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

[A.D. Smirnov, Phys. Lett. B **346** (1995); Ya.F. **58** (1995)]

➞ Higgs mechanism ➞ Scalar Leptoquarks ➞

$$S^{(\pm)} = \begin{pmatrix} S^{(+)}_{1\alpha} \\ S^{(+)}_{2\alpha} \end{pmatrix}; \begin{pmatrix} S^{(-)}_{1\alpha} \\ S^{(-)}_{2\alpha} \end{pmatrix}; \qquad Q_{em} = \begin{pmatrix} 5/3 \\ 2/3 \end{pmatrix}; \begin{pmatrix} 1/3 \\ -2/3 \end{pmatrix}.$$

➞ LFV Processes $l_i \to l_j \gamma$

1. Introduction

Current limits from direct search: $M_{LQ} \sim 200 - 300$ GeV,

Indirect limits from $K_L^0 \to \mu^\pm e^\mp$, S, T, U parameters,

$g - 2$ and others close to direct limits

Other source ➞ LFV Processes

Exist strong experimental limits

$$Br(\mu \to e\gamma) < 1.2 \cdot 10^{-11}$$

[M.Ahmed et al., (MEGA Collab) PRD **65** (2002):

$$Br(\tau \to \mu\gamma) < 4.5 \cdot 10^{-8}$$

[K.Hayasaka et al., (Belle Collab) ArXiv:0705.0650]

$$Br(\tau \to e\gamma) < 3.3 \cdot 10^{-8}$$

[E.Guido, Moriond 2010]

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$$Br(l_i \to l_j\gamma) \to m_{S_a^{(\pm)}} \to ?$$

2. Minimal Quark-Lepton Symmetry Model

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

(A. D. Smirnov, Phys. Lett. B **346**, YaF**58** 1995.)

$$\psi^{L,R}_{iaA} \sim (4, 2, Y^R_a),$$

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

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

where $a = 1, 2$ – $SU_L(2)$ index, A=α,4, $\alpha = 1, 2, 3$ – $SU_c(3)$ index
$i, j = 1, 2, 3$ – indices of generations

$$C_Q = (A^L_{Q_1})^+ A^L_{Q_2} \equiv V_{CKM} \qquad C_l = (A^L_{l_1})^+ A^L_{l_2} \equiv U^+_{PMNS}$$

$$K^{L,R}_a = (A^{L,R}_{Q_a})^+ A^{L,R}_{l_a}$$

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2.Model: Scalar Sector

$$(4,1,1), \qquad (1,2,1), \qquad (15,2,1), \qquad (15,1,0)$$

$$\eta_1 \qquad \eta_2 \qquad \eta_3 \qquad \eta_4$$ – VEV,

$$\tan\beta = \eta_3/\eta_2 \qquad \eta = \sqrt{\eta_2^2 + \eta_3^2} \approx 250 \text{ GeV}$$ – SM VEV

2. Model

The interactions give contributions into $l_i \to l_j \gamma$

$$\mathcal{L}_{S_1^{(+)} u_i l_j} = \bar{u}_{i\alpha} \left[(h_+^L)_{ij} P_L + (h_+^R)_{ij} P_R \right] l_j \, S_{1\alpha}^{(+)} + \text{h.c.}$$

$$\mathcal{L}_{S_m d_i l_j} = \bar{d}_{i\alpha} \left[(h_{2m}^L)_{ij} P_L + (h_{2m}^R)_{ij} P_R \right] l_j \, S_{m\alpha} + \text{h.c.}$$

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

$$S_2^{(+)} = \sum_m c_m^{(+)} S_m, \qquad \overset{*}{S}{}_2^{(-)} = \sum_m c_m^{(-)} S_m,$$

where $c_m^{(\pm)}$, $m = 0, 1, 2, 3$ are the elements of the unitary scalar leptoquark mixing matrix.

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2. Model

Because of Higgs origin the coupling constants are proportional to the ratios of fermionic masses to the SM VEV

$$m_u/\eta \sim m_d/\eta \sim 10^{-5} \qquad m_s/\eta \sim 10^{-3}$$

$$m_c/\eta \sim m_b/\eta \sim 10^{-2} \qquad m_t/\eta \sim 0.7$$

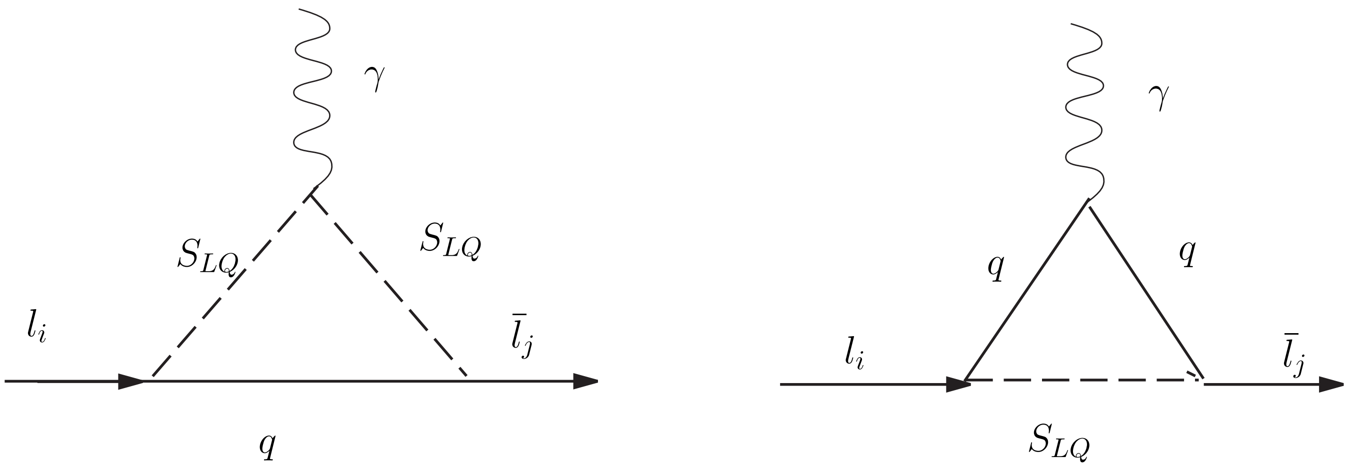
The dominant coupling constants are

$$\begin{aligned}
(h_+^L)_{3j} &= \frac{\sqrt{6}\, m_t}{2\eta \sin\beta} (K_1^L C_l)_{3j}, \\
(h_+^R)_{3j} &= -\frac{\sqrt{6}\, m_b}{2\eta \sin\beta} (C_Q)_{33} (K_2^R)_{3j}, \\
(h_{2m}^{L,R})_{3j} &= -\frac{\sqrt{6}\, m_b}{2\eta \sin\beta} (K_2^{L,R})_{3j}\, c_m^{(\mp)},
\end{aligned}$$

i.e. SLQs of MQLS model are like LQ of 3-d generation.

[P.Yu. Popov, A.V. Povarov and A.D. Smirnov, MPL**A20** (2005).]

3. Widths of $l_i \to l_j\gamma$ decays



Diagrams representing the contribution of scalar leptoquarks (SLQ) into the $l_i \to l_j\gamma$ Processes: $q = u_i(d_i)$ is the up(down) quark of the ith generation and $S_{LQ} = S_1^{(+)}(S_m)$ is the SLQ corresponding to the above quarks.

Contributions of S_m and b-quark in the amplitude $l_i \to l_j\gamma$ suppress by m_b^2/m_t^2 comparing with ones of $S_1^{(+)}$ and t-quark

3.Widths

General form of the $l_i \to l_j\gamma$ amplitude (one loop approximation)

$$
\begin{aligned}
M &= -\frac{|e|}{64\pi^2 m_{LQ}^2}\bar{l}_j \sigma^{\mu\nu} q^{\nu}\Bigg[m_i \Big(Q_k F_4(x) - Q_s F_2(x)\Big)\Big((|h_+^L|^2)_{ji} P_R + (|h_+^R|^2)_{ji} P_L\Big) \\
&+ 2m_k \Big(Q_k F_3(x) - Q_s F_3(x)\Big)\Big((\overset{+}{h}{}_+^L h_+^R)_{ji} P_R + (\overset{+}{h}{}_+^R h_+^L)_{ji} P_L\Big)\Bigg] l_i \epsilon^{\mu},
\end{aligned}
$$

Decay probability

$$
\begin{aligned}
W(l_i \to l_j\gamma) &= \frac{9\alpha m_i}{256(4\pi)^4}\left(\frac{m_i}{\eta}\right)^4 x^2 \Bigg(B_1^2(x) k_{ij}^{(1)} + 4\left(\frac{m_b}{m_i}\right)^2 B_2^2(x) k_{ij}^{(2)} \\
&- 2\frac{m_b}{m_i} B_1(x) B_2(x) Re(k_{ij}^{(12)})\Bigg), \\
B_1(x) &= Q_k F_4(x) - Q_S F_2(x), \qquad B_2(x) = Q_k F_3(x) - Q_S F_1(x),
\end{aligned}
$$

where Q_k, Q_S are electric charge of q_k-quark and LQ, and $x = m_k^2/m_{LQ}^2$

3.Widths: functions

$$F_2(x) = \frac{1}{6(1-x)^4}(1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x),$$

$$F_3(x) = \frac{1}{(1-x)^3}(1 - x^2 + 2x \ln x),$$

$$F_5(x) = \frac{1}{6(1-x)^4}(2 + 3x - 6x^2 + x^3 - 6x \ln x),$$

$$F_6(x) = \frac{1}{(1-x)^3}(-3 + 4x - x^2 - 2 \ln x).$$

where $x = m_k^2/m_{LQ}^2$

3.Widths: matricies

$$k_{ij}^{(1)} = \frac{|(K_1^L C_l)_{3j}|^2 |(K_1^L C_l)_{3i}|^2}{\sin^4\beta},$$

$$k_{ij}^{(2)} = \frac{1}{\sin^4\beta}\left(|(K_1^L C_l)_{3j}|^2 |(K_2^R)_{3i}|^2 + (i \leftrightarrow j)\right),$$

$$k_{ij}^{(12)} = \frac{1}{\sin^4\beta}\Big((|(K_1^L C_l)_{3j}|^2 + |(K_2^R)_{3j}|^2) \times$$

$$\times \; ((K_1^L C_l)^*_{3i}(K_2^R)_{3i} + (K_2^R)^*_{3i}(K_1^L C_l)_{3i}) + (i \leftrightarrow j)\Big).$$

4. Numerical Results and Discussion.

$$Br(\mu \to e\gamma) = 1.1 \times 10^{-4} x^2 \Big(B_1^2(x) k_{\mu e}^{(1)} - $$
$$- 84 B_1(x) B_2(x) Re(k_{\mu e}^{(12)}) + 7056 B_2^2(x) k_{\mu e}^{(2)} \Big),$$
$$Br(\tau \to e\gamma) = 2.2 \times 10^{-5} x^2 \Big(B_1^2(x) k_{\tau e}^{(1)} - $$
$$- 4.8 B_1(x) B_2(x) Re(k_{\tau e}^{(12)}) + 20 B_2^2(x) k_{\tau e}^{(2)} \Big),$$
$$Br(\tau \to \mu\gamma) = 2.2 \times 10^{-5} x^2 \Big(B_1^2(x) k_{\tau \mu}^{(1)} - $$
$$- 4.8 B_1(x) B_2(x) Re(k_{\tau \mu}^{(12)}) + 20 B_2^2(x) k_{\tau \mu}^{(2)} \Big).$$

4.Numerical Results: Variant I

I) Main Contribution

$$Br(\mu \to e\gamma) = 0.7x^2 B_2^2(x) k_{\mu e}^{(2)},$$

$$k_{\mu e}^{(2)} = \frac{1}{\sin^4\beta}\left(|(K_1^L C_l)_{3e}|^2 |(K_2^R)_{3\mu}|^2 + (\mu \leftrightarrow e) \right),$$

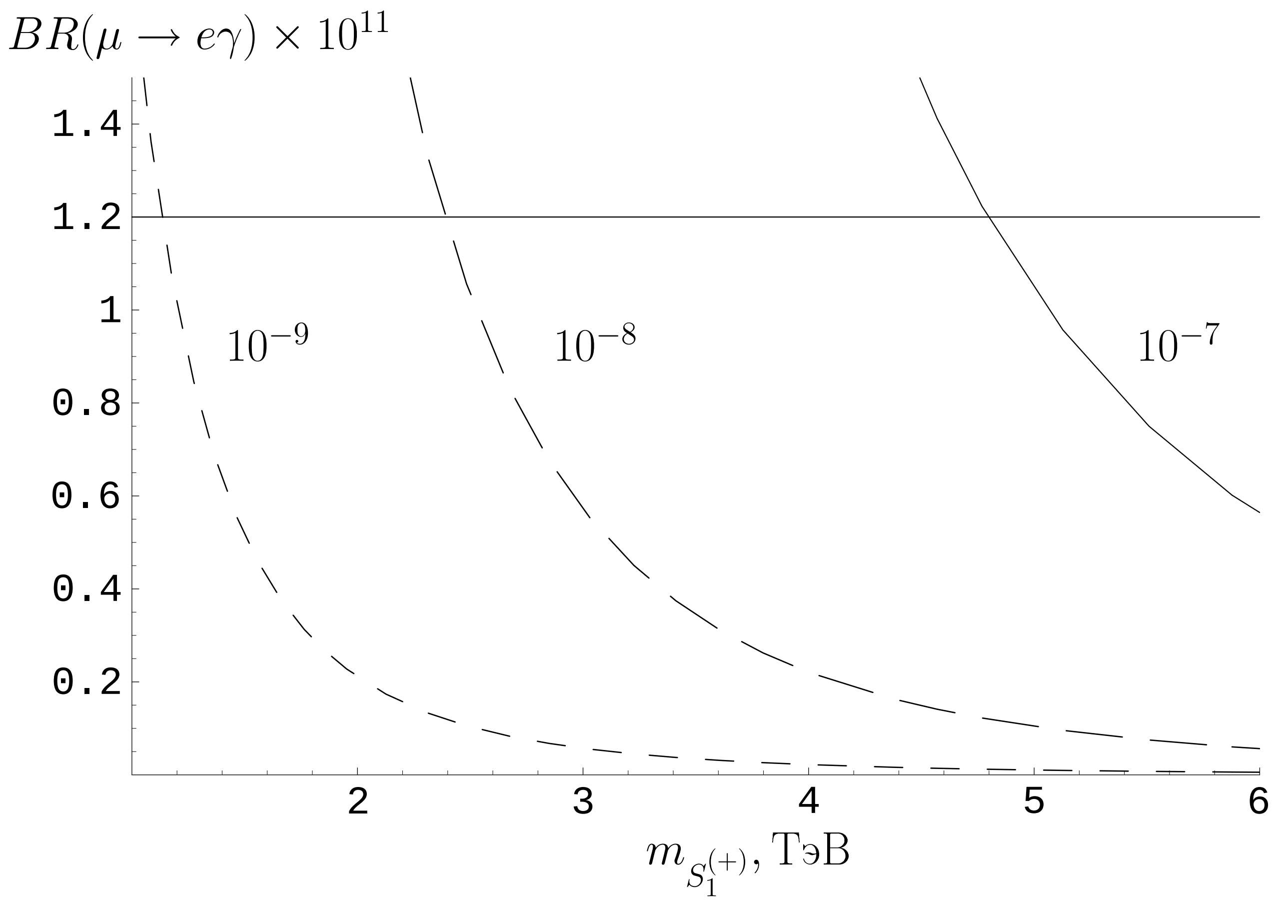
The Lower Limit on Mass Scalar Leptoquark $S_1^{(+)}$ from Decay $\mu \to e\gamma$ for Different Value of Parameter $k_{\mu e}^{(2)}$.

$k_{\mu e}^{(2)}$	2.5×10^{-12}	10^{-11}	10^{-10}	10^{-6}
$m_{S_1^{(+)}}$ TeV	0.2	0.5	1	16

$$(K_2^R)_{13}, (K_1^L C_l)_{13} \sim 10^{-3}, \quad (K_2^R)_{23}, (K_1^L C_l)_{23} \sim 10^{-2}$$

$$m_{S_1^{(+)}} \sim 1 \text{ TeV}$$

4.Numerical Results: Variant I



The Lower Limit on Mass Scalar Leptoquark $S_1^{(+)}$ resulting from $BR(\mu \to e\gamma)$ with Value of Parameter $k_{\mu e}^{(2)} = 10^{-9}, 10^{-8}, 10^{-7}$ (Horizontal line corresponds experimental limit $Br(\mu \to e\gamma) < 1.2 \cdot 10^{-11}$)

4.Numerical Results: Variant II

II) Variant with $K_2^R = I$

$$Br(\mu \to e\gamma) = 1.1 \times 10^{-4} x^2 B_1^2(x) k_{\mu e}^{(1)},$$

$$k_{\mu e}^{(1)} = \frac{|(K_1^L C_l)_{3e}|^2 |(K_1^L C_l)_{3\mu}|^2}{\sin^4 \beta}.$$

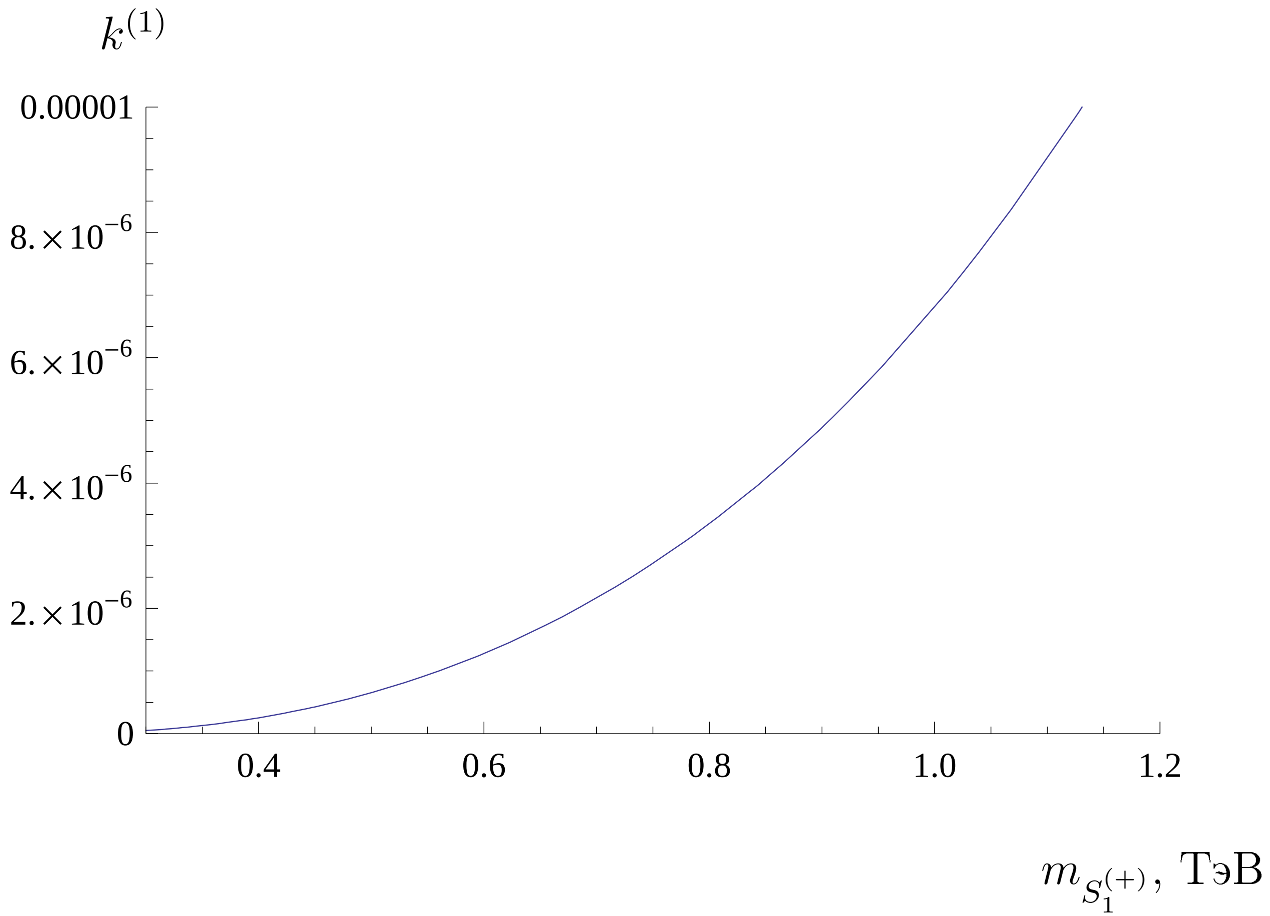
Lower limit on scalar leptoquark $S_1^{(+)}$ mass resulting from $\mu \to e\gamma$ with $K^R = I$ for different values of parameter $k_{\mu e}^{(1)}$

$k_{\mu e}^{(1)}$	10^{-8}	10^{-6}	10^{-5}	10^{-4}	0.01	1
$m_{S_1^{(+)}}$ TeV	0.25	0.55	1.1	2.4	9.3	34

$$(K_1^L C_l)_{13} \sim 10^{-2}, \qquad (K_1^L C_l)_{23} \sim 0.1$$

$$m_{S_1^{(+)}} \sim 1 \text{ TeV}$$

4.Numerical Results: Variant II



The allowed region of parameters $m_{S_1^{(+)}}$ and $k^{(1)}_{\mu e}$ resulting from $BR(\mu \to e\gamma)$ with $K^R = I$(below the curve) .

4.Numerical Results: Variant IIa

IIa) Case with $K_2^L = K_2^R = I, \quad C_l^+ = U_{PMNS} \equiv U$

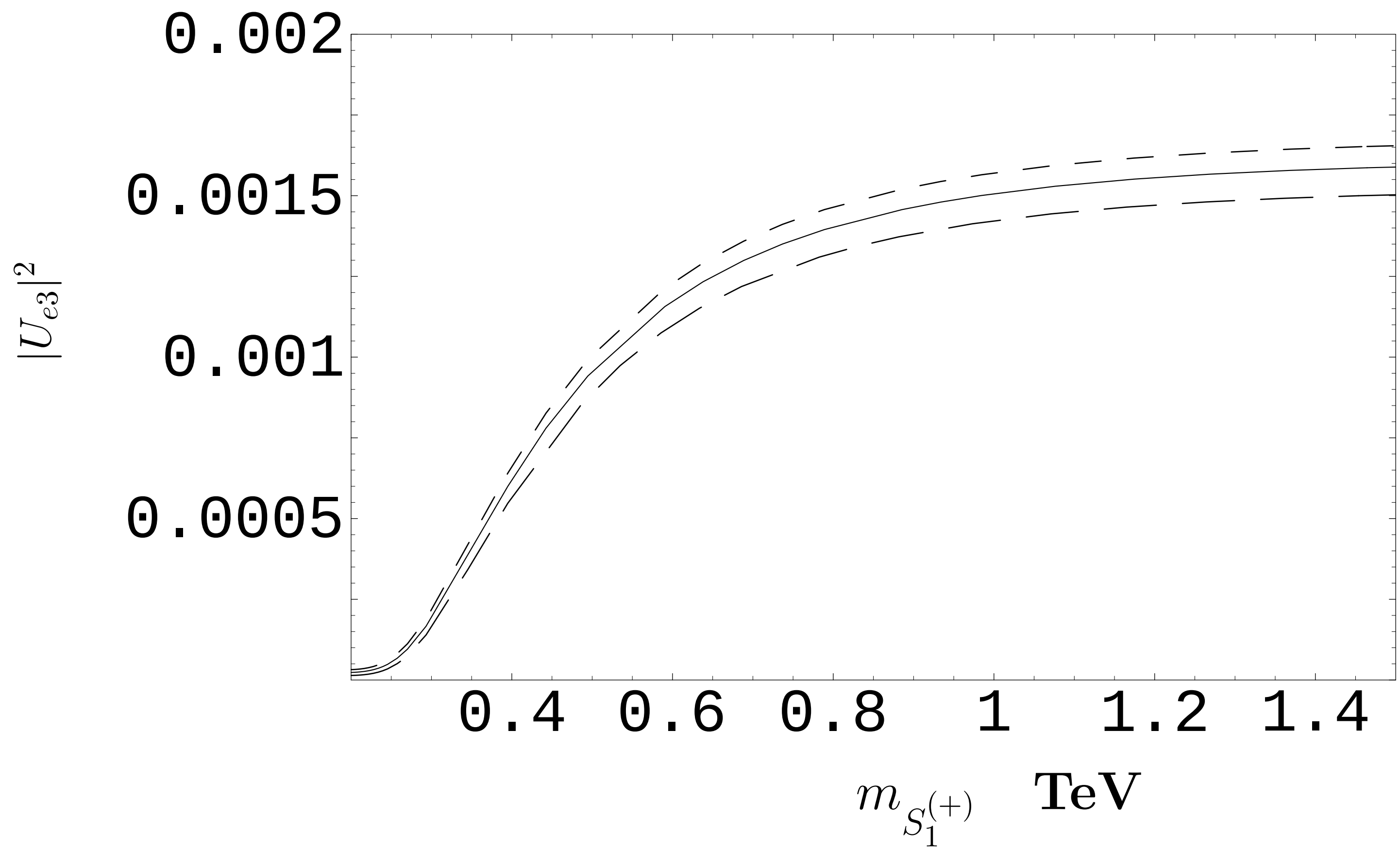
$$k_{\mu e}^{(1)} = \frac{|(U)_{13}|^2 |(U)_{23}|^2}{\sin^4 \beta}.$$

Upper limit on the matrix element U_{13} resulting from process $\mu \to e\gamma$ with $K^{R,L} = I$ in dependence on $\sin\beta$ and $S_1^{(+)}$ mass

$m_{S_1^{(+)}}$ TeV	0.55	1.3	9.3
$\sin\beta = 0.2$	6×10^{-5}	2×10^{-4}	6×10^{-3}
$\sin\beta = 1$	1×10^{-3}	5×10^{-3}	0.14

$U_{23} = 0.7$ [W.L. Guo and Z.Z. Xing, PRD**67**, (2003); M.C. Gonzalez-Garcia and C. Pena-Garay, PRD.**68**, (2003).]

4.Numerical Results: Variant IIa



Upper limit on the matrix element U_{13} resulting from $\mu \to e\gamma$ with $K^{R,L} = I$ as function of $S_1^{(+)}$ mass at $U_{23} = 0.7^{+0.12}_{-0.16}$ and $\sin\beta = 1$. Current experimental limit is $|U_{13}|^2 < 0.032$ (G. Fogli et al., Prog. Part. Nucl. Phys. 57 (2006)) .

4.Numerical Results: Variants III-IV

III) Variant with $(K_1^L C_l)_{13} = 0, \qquad (K_2^R)_{13} = 0$

$$Br(\tau \to \mu\gamma) < 4.5 \cdot 10^{-8}$$

Lower Limit on the $S_1^{(+)}$ Mass resulting from $\tau \to \mu\gamma$ in dependence on $k_{\tau\mu}^{(1)} = k_{\tau\mu}^{(2)} = k_{\tau\mu}^{(12)}$

$k_{\tau\mu}^{(1)} = k_{\tau\mu}^{(2)} = k_{\tau\mu}^{(12)}$	10^{-4}	10^{-3}	10^{-2}
$m_{S_1^{(+)}}$ TeV	0.3	0.7	1.4

IV) Interaction of scalar leptoquark $S_m \quad (Q = 2/3)$ gives the lower limit on m_{S_m} weaker than the current experimental ones

V) The Case of the chiral interaction of scalar leptoquarks $S_1^{(+)}$ with fermions gives the limits which coincide with those of the [Variant II]

Conclusions

The contributions of scalar leptoquarks $S_1^{(+)}$, S_m from the MQLS model in $l_i \to l_j\gamma$ decays are analysed in comparison with experimental data on $\mu \to e\gamma,\ \tau \to \mu\gamma,\ \tau \to e\gamma$ decays

It is shown that in the appropriate region of the mixing parameters relatively light scalar leptoquarks (with masses of order 1 TeV or below) do not contradict current experimental restrictions on LFV processes