Analysis of $B \to K_1 ll$ process in the scalar leptoquark model

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Abstract

We investigate the effect of scalar leptoquark on the rare semileptonic $B \to K_1 ll$ decay mode. We constrain the leptoquark coupling by using the updated experimental limits on the branching ratios of $b \to sll$ process and the lepton nonuniversality $R_{K^{(*)}}$ parameters. Using the constrained new parameters, we estimate the branching ratios, forward-backward asymmetry, lepton non-universality parameters of $B \to K_1 ll$ channel.

Standard Model

	Field	$SU(3)_C \times SU(2)_L \times U(1)_Y$
Fermions	$Q_L \equiv (u,d)_L^T$	$(\mathbf{3},\mathbf{2},\ 1/6)$
	u_R	$(\mathbf{3},\mathbf{1},\ 2/3)$
	d_R	$(\mathbf{3},\mathbf{1},\ -1/3)$
	$e_L \equiv (\nu_e,\ e)_L^T$	$(\mathbf{1},\mathbf{2},\ -1/2)$
	e_R	$(\mathbf{1},\mathbf{1},\ -1)$
	$\mu_L \equiv (\nu_\mu,\ \mu)_L^T$	$(\mathbf{1},\mathbf{2},\ -1/2)$
	μ_R	$(\mathbf{1},\mathbf{1},\ -1)$
	$\tau_L \equiv (\nu_\tau,\ \tau)_L^T$	$(\mathbf{1},\mathbf{2},\ -1/2)$
	τ_R	$(\mathbf{1},\mathbf{1},\ -1)$
Scalars	H	$(\mathbf{1},\mathbf{2},\ 1/2)$

Table 1:SM gauge particles

Failure of SM

SM is not a completely successful theory. It has some limitations , those are

- It doesn't give any explaination about why do we have only three generations of quarks and leptons.
- Why there is a mass hierarchy between 3 generations of elementary particles?
- In SM, neutrino oscillation is not allowed. But we experimentally observed the neutrino oscillation.
- In SM, we neglected gravitational force.
- This theory doesn't give any clues for Dark matter and Dark energy.

Anomalies

In addition to this common limitations of SM there are some anamolies exist in B-meson sector. Anamolies in rare semileptonic B meson decays are :

- 2.5σ deviation found in R_K value of $B^+ \to K^+ l^+ l^-$ process.
- In $\bar{B} \to \bar{K}^* l^+ l^-$ decay, we observe 3σ deviation in decay rate and P_5' observable.
- LHCb collaboration reported that , 2.2σ and 2.4σ inconsistency exist between experimentally and SM values of R^* in $q^2 \in [0.045, 1.1] GeV^2$ and $q^2 \in [1.1, 6] GeV^2$ respectively.
- Around 3.3σ deviation observed in R_D and D_{D^*} values.
- 3.9σ discrepancy in decay distribution of $B_s \to \phi\mu^+\mu^-$
- We experimentally observed lepton flavor violation in some decay process such as $\mu^- \to e^-\gamma, \tau^- \to l^-\gamma, \tau^- \to 3\mu^-(e^-), B_{s,d} \to l_i^\mp l_j^\pm, B^+ \to K^+(\pi^+) l_i^\mp l_j^\pm$. But this flavour violation is forbidden in Standard model.

Leptoquark model

- Leptoquarks (LQ) are the hypothetical particle which can couple with both leptons and quarks.
- Currently mass of LQ is not determined yet. We found experimental lower bounds for different generations of Leptoquarks.
- 6 types of scalar LQ and 6 type of vector LQ's are exist.
- Scalar LQ's are spin zero particles, while vector LQ's are spin one particles.
- Both scalar and vector leptoquarks give the contribution for B meson decay.
- Although many LQ gives direct contribution to B meson decay at tree level, here we only consider contributions of S_2 and $\tilde{S}_2$ to rare B-meson decay.

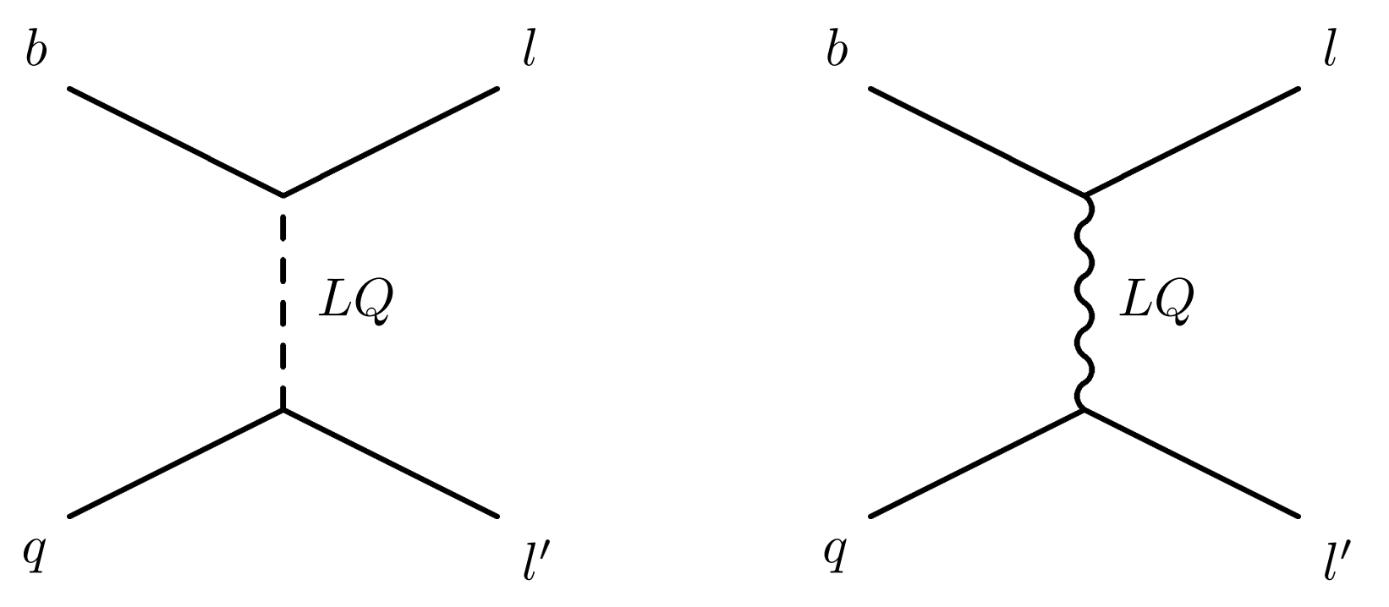

Figure 1:Feynman diagram for $b \to sll'$ process mediated by scalar[left panel] and vector[right panel] LQ .

$S_2(3, 2, 7/6)$

Yukawa coupling of S_2 with SM fermions are given by:

$$\mathcal{L} = -\lambda_{RL}^{ij} \bar{u}_R^i S_{2\alpha}^T \in_{\alpha\beta} L_{\beta L}^j - \lambda_{LR}^{ij} \bar{e}_R i S_{2\alpha}^\dagger Q_{\alpha L}^j + h.c \tag{1}$$

Where, $i, j = 1, 2, 3$ and $\alpha, \beta = 1, 2$ also $\in = i\sigma_2$.
Multiplets can be expressed as

$$S_2 = \begin{pmatrix} S_2^{5/3} \\ S_2^{2/3} \end{pmatrix}, Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \in = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \tag{2}$$

Expanding $SU(2)_L$ indices in above equation is given by:

$$\begin{aligned} \mathcal{L} = &-\lambda_{RL}^{ij} \bar{u}_{\alpha R}^i S_{2\alpha}^{\frac{5}{3}} e_L^j + [\lambda_{RL} V_{PMNS}]^{ij} u_{\alpha R}^i S_{2\alpha}^{\frac{2}{3}} \nu_L^j \\ &-[\lambda_{LR} V_{CKM}]^{ij} \bar{e}_R^i S_{2\alpha}^{\frac{5}{3}\dagger} u_{\alpha L}^j - \lambda_{LR}^{ij} \bar{e}_R^i S^{\frac{2}{3}\dagger} d_{\alpha L}^j + h.c \end{aligned} \tag{3}$$

Interaction hamiltonian is given by:

$$\mathcal{H}_{LQ} = \frac{\lambda_{LR}^{i3} \lambda_{LR}^{ik*}}{8M^2_{S_2^{\frac{2}{3}}}} [\bar{q}\gamma^\mu (1-\gamma_5) b][\bar{l}\gamma_\mu (1+\gamma_5) l] \equiv \frac{\lambda_{LR}^{i3} \lambda_{LR}^{ik*}}{4M^2_{S_2^{\frac{2}{3}}}} (\mathcal{O}_9 + \mathcal{O}_{10}) \tag{4}$$

Compare LQ and SM hamiltonian , we get

$$\mathcal{H}_{LQ} = -\frac{G_F \alpha_{em}}{\sqrt{2}\pi} V_{tb} V_{tq}^* (C_9^{LQ} \mathcal{O}_9 + C_{10}^{LQ} \mathcal{O}_{10}) \tag{5}$$

We get new Wilson's coefficient

$$C_9^{LQ} = C_{10}^{LQ} = -\frac{\pi}{2\sqrt{2} G_F \alpha_{em} V_{tb} V_{tq}^*} \frac{\lambda_{LR}^{i3} \lambda_{LR}^{ik*}}{8M^2_{S_2^{\frac{2}{3}}}} \tag{6}$$

Where k and i are the generation index of the quark flavor q and lepton l respectively.

$\tilde{S}_2(3, 2, 1/6)$

Coupling of $\tilde{S}_2$ with leptons and quarks are given by:

$$\mathcal{L} = -\lambda_{RL}^{ij} \bar{d}_{\alpha R}^i \tilde{S}_{2\alpha}^T \in_{\alpha\beta} L_{\beta L}^j + h.c \tag{7}$$

Where $\tilde{S}_2 = \left(\tilde{S}_2^{\ 2/3} \ \ \tilde{S}_2^{\ -1/3} \right)^T$ .By expanding the indices we get,

$$\mathcal{L} = -\lambda_{RL}^{ij} \bar{d}_{\alpha R}^i \tilde{S}_{2\alpha}^{2/3} e_L^j + [\lambda_{RL} V_{PMNS\nu}]^{ij} \bar{d}_{\alpha R}^i \tilde{S}_{2\alpha}^{-1/3} \nu_L^j \tag{8}$$

Interaction hamiltonian after applying the Feirz transformation is given by:

$$\mathcal{H}_{LQ} = \frac{\lambda_{RL}^{ik} \lambda_{RL}^{3i*}}{8M^2_{S_2^{\frac{2}{3}}}} [\bar{q}\gamma^\mu (1+\gamma_5) b][\bar{l}\gamma_\mu (1+\gamma_5) l] \equiv \frac{\lambda_{RL}^{ki} \lambda_{RL}^{3i*}}{4M^2_{S_2^{\frac{2}{3}}}} (\mathcal{O}_9' + \mathcal{O}_{10}') \tag{9}$$

$\tilde{S}_2$ contribution to new Wilson's coefficients are given by:

$$C_9'^{LQ} = -C_{10}'^{\ LQ} = -\frac{\pi}{2\sqrt{2} G_F \alpha_{em} V_{tb} V_{tq}^*} \frac{\lambda_{RL}^{ki} \lambda_{RL}^{3i*}}{8M^2_{S_2^{\frac{2}{3}}}} \tag{10}$$

One can get $\mathcal{O}_9'$ and $\mathcal{O}_{10}'$ operators by replacing $L \leftrightarrow R$ in $\mathcal{O}_9$ and $\mathcal{O}_{10}$

Constraints on LQ coupling

We can calculate the constraints of NP parameters by using rare B meson decay such as $B_{s,d} \to l^+l^-, \bar{B} \to X_s l^+ l^-$ and $B_s^0 - bar B_s^0$ mixing data.

$B_s \to \mu^+\mu^-$ process:

Since FCNC is not allowed in SM this process occurs at one loop level, but in NP it occurs at tree level also we get the NP constraint value from this process. In this rare leptonic decay we get only C_{10}^{NP} value.
Effective hamiltonian for $B_s \to \mu^+\mu^-$ is given by:

$$\mathcal{H}_{eff} = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{tq}^* [C_{10}^{eff} \mathcal{O}_{10} + C_{10}' \mathcal{O}_{10}'] \tag{11}$$

Where $C_{10}^{eff} = C_{10}^{SM} + C_{10}^{NP}$. Branching ratio is given by:

$$BR = \frac{G_F^2}{16\pi^3} \tau_{B_q} \alpha^2 f_{B_q}^2 M_{B_q} m_\mu^2 |V_{tb} V_{tq}^*|^2 |C_{10}^{eff} - C_{10}'|^2 \sqrt{1 - \frac{4m_\mu^2}{M_{B_q}^2}} \tag{12}$$

Transition amplitude by considering leptoquark model is given by:

$$\mathcal{M} = -\frac{G_F}{\sqrt{2}\pi} V_{tb} V_{tq}^* \alpha f_{B_q} M_{B_q} m_\mu C_{10}^{SM} P \tag{13}$$

where,

$$P \equiv \frac{C_{10} - C'10}{C_{10}^{SM}} = re^{i\phi} \tag{14}$$

From above equation , branching ratio for new physics is given by:

$$BR(B_s \to \mu^+\mu^-)_{th} = BR(B_s \to \mu^+\mu^-)_{SM} (1 + r^2 - 2r\cos\phi) \tag{15}$$

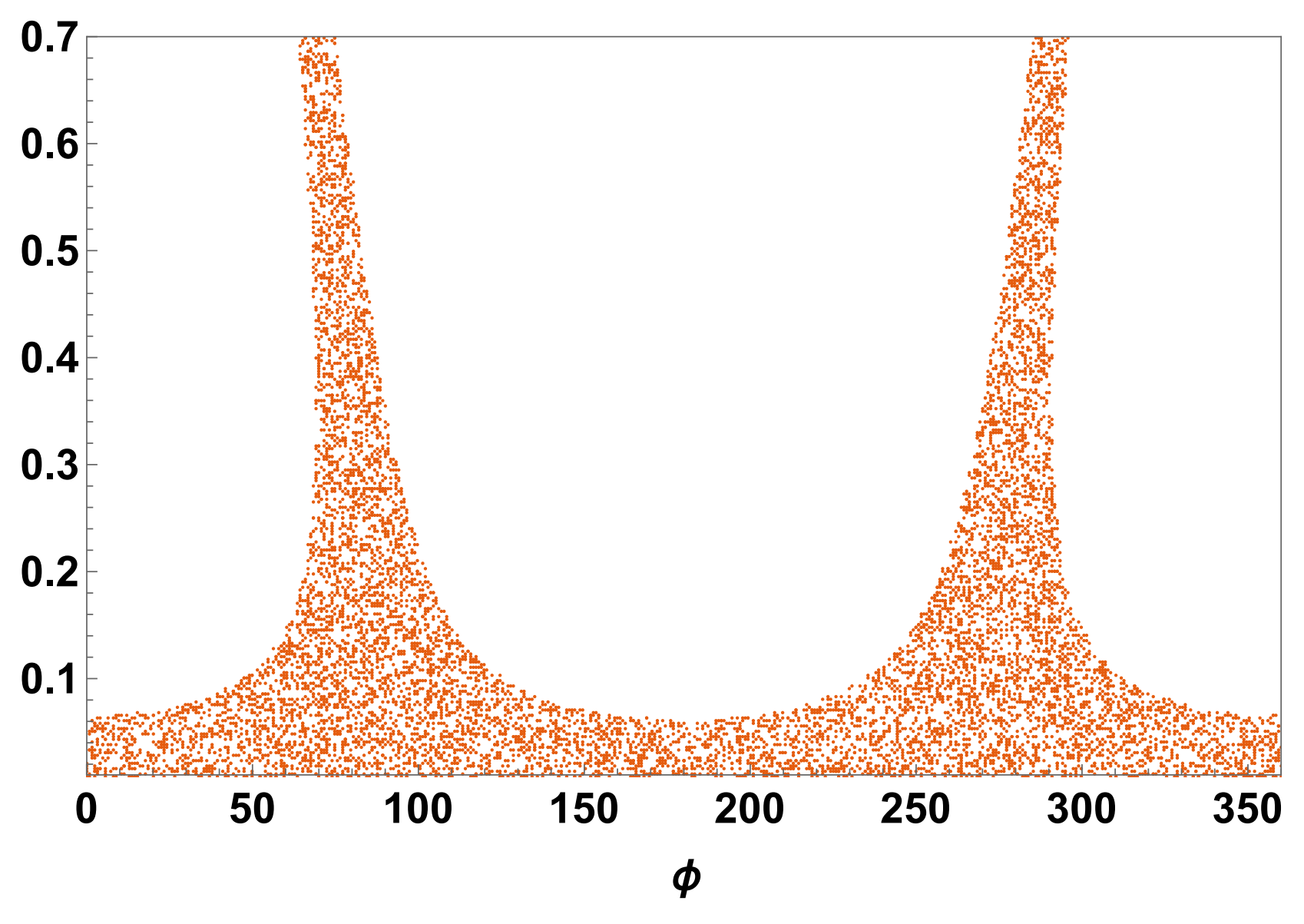

Figure 2:allowed range for $r - \phi$.

The updated SM branching ratio value including all the correction is:

$$BR(B_s \to \mu^+\mu^-)_{SM} = (3.65 \pm 0.23) \times 10^{-9} \tag{16}$$

The allowed range of $r - \phi$ calculated for 2σ range is :

$$0 \leqslant r \leqslant 0.7 \qquad and \qquad 0 \leqslant \phi \leqslant 2\pi \tag{17}$$

$B \to K_1 l^+ l^-$

Here we consider decay of B meson to axial vector mesons $K_1(1270)$ and $K_1(1400)$. These two states are admixture of 1^3P_1 and 1^1P_1 states i.e K_{1A} and K_{1B} and those are related by the equation below:

$$\begin{pmatrix} K_1(1270) \\ K_1(1400) \end{pmatrix} = M \begin{pmatrix} K_{1A} \\ K_{1B} \end{pmatrix} \tag{18}$$

where, $M = \begin{pmatrix} \sin\theta & \cos\theta \\ \cos\theta & -\sin\theta \end{pmatrix}$ and θ is the mixing angle and it's predicted value is $-(34 \pm 13)^\circ$

Observables

① **Differential decay rate:**

Differential decay rate of $B^+ \to K_1^+ l^+ l^-$ with respect to dilepton invariant mass i,e q^2 is given by:

$$\frac{d\Gamma(B \to K_1 ll)}{d\hat{s}} = \frac{G_F^2 \alpha_{em}^2 m_B^2}{2^{10}\pi^5} |V_{tb} V_{ts}^*|^2 \hat{u}(\hat{s}) \Delta \tag{19}$$

② **LFU Violating observable:**

Lepton flavour violating observables for $B^+ \to K_1^+ \mu^+ \mu^-$ is given by:

$$R_{K1}^{\mu e} = \frac{dBr(B^+ \to K_1^+ \mu^+ \mu^-)/dq^2}{dBr(B^+ \to K_1^+ e^+ e^-)/dq^2} \tag{20}$$

We can calculate R_K value for $\mu - \tau$ also

$$R_{K_1}^{\tau\mu} = \frac{dBr(B^+ \to K_1^+ \tau^+ \tau^-)/dq^2}{dBr(B^+ \to K_1^+ \mu^+ \mu^-)/dq^2} \tag{21}$$

In SM this value is 1 because coupling is irrespective of lepton flavour.

③ R_μ **observable:**

$$R_\mu = \frac{dBr(B^+ \to K_1(1400) \mu^+ \mu^-)/dq^2}{dBr(B^+ \to K_1(1270) \mu^+ \mu^-)/dq^2} \tag{22}$$

Above observable can be used for determining the mixing angle θ of K_1 mesons.

Plots for observables are show below, left panel corresponds to $K_1(1270)$ and right panel for $K_1(1400)$

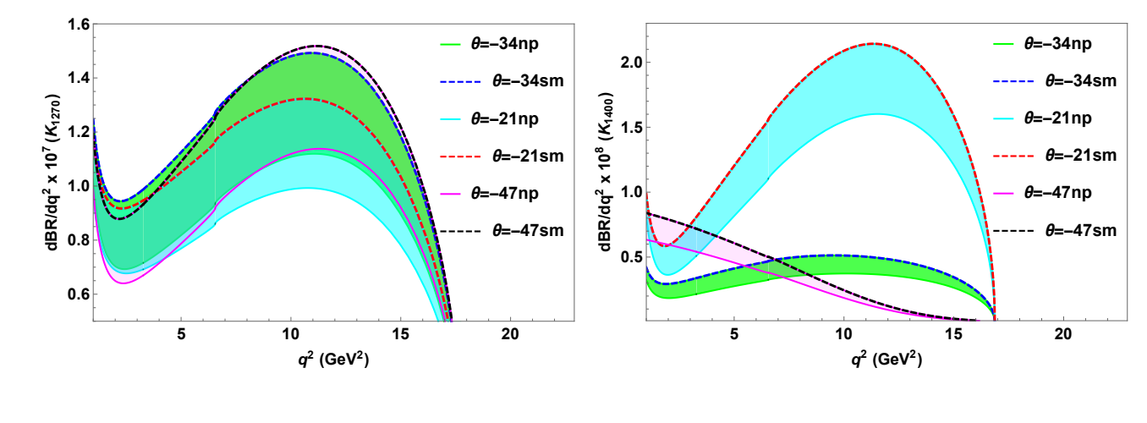

Figure 3:Variation of branching ratio w.r.t q^2 for different angles .

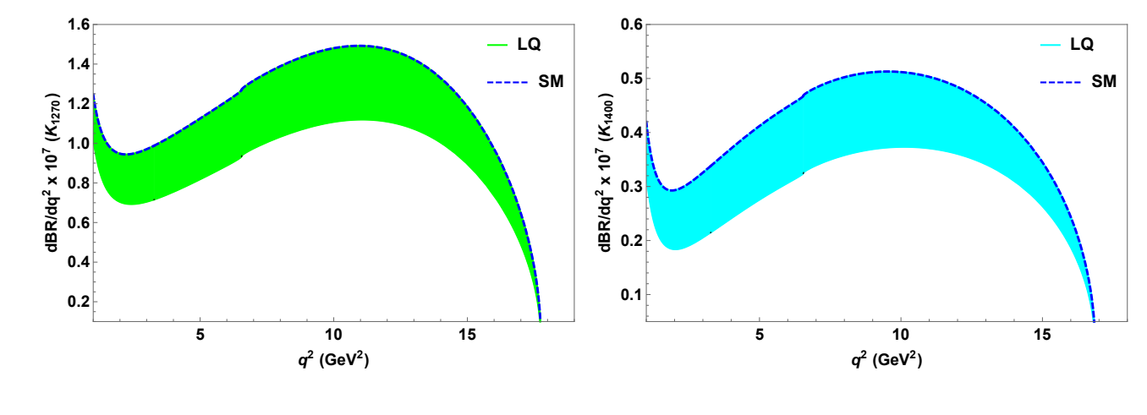

Figure 4:Variation of branching ratio with q^2 for $\theta = -34^\circ$.

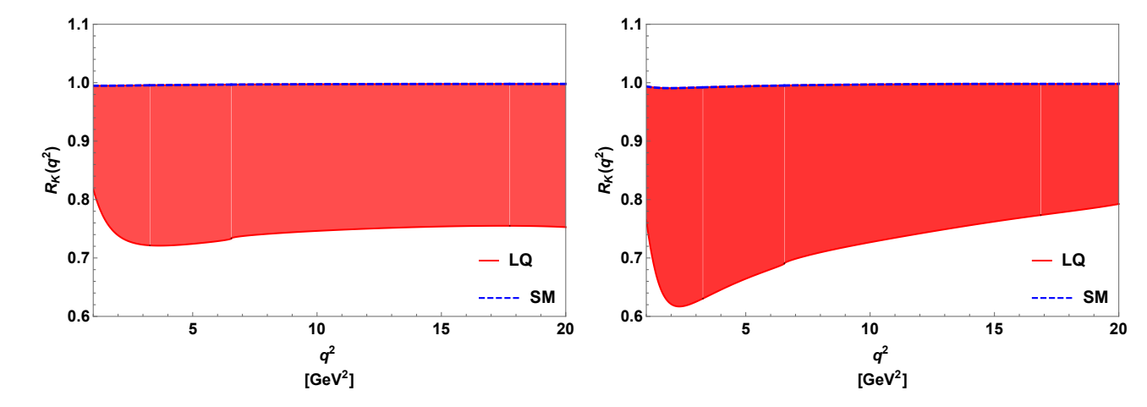

Figure 5:Variation of $R_K^{\mu e}$ with q^2 for $\theta = -34^\circ$.

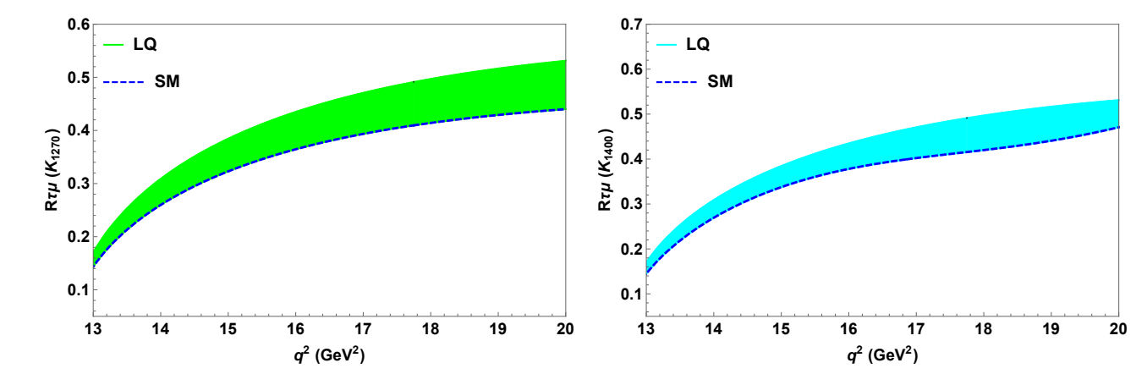

Figure 6:Variation of $R_K^{\tau\mu}$ with q^2 for $\theta = -34^\circ$.

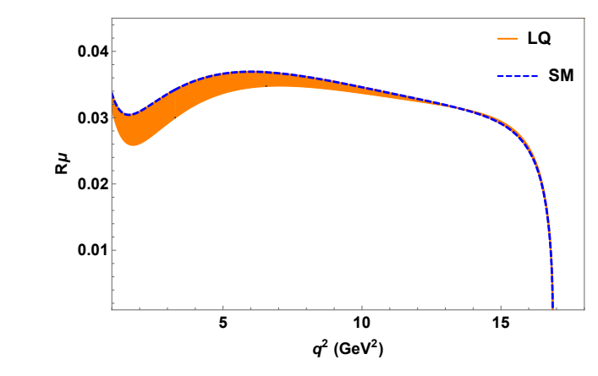

Figure 7:Variation of R_μ with q^2 for $\theta = -34^\circ$.

Conclusion

- We have investigated $B \to K_1 ll$ process using scalar LQ model.By using the NP constraint from $B_s \to l+l^-$ process .
- By applying NP we are getting some deviation in Branching ratio, $R_K^{\mu e}$ and $R_K^{\tau\mu}$ which are closer to experimentally measured value compared to that of SM value.
- This is the one of the indication of existence of new physics.

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