Explanation of $B \to K^{*}\ell^{+}\ell^{-}$ and muon g-2 anomalies with leptoquarks

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In collaboration with

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based on the work in PRD92(16)

Motivation to search for new physics:

- ❑ Some unsolved problems, such as neutrino mass, dark matter, matter-antimatter asymmetry, cannot be explained in the SM, the SM is an effective theory at the electroweak scale

- ❑ It will be exciting if any excesses from the SM predictions are found in experiments

- ❑ Some data with more than 3σ deviations from the SM predictions were shown over the past few years: for instance,

➢ muon anomalous magnetic dipole moment, muon g-2

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (28.8 \pm 8.0)\times 10^{-10} \;\; PDG$$

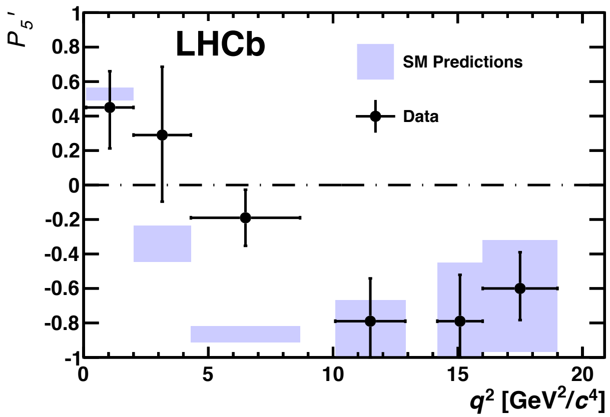
- Angular observable P_5' of $B \to K^* \mu^+ \mu^-$:

Descotes-Genon etal, JHEP1301(13)

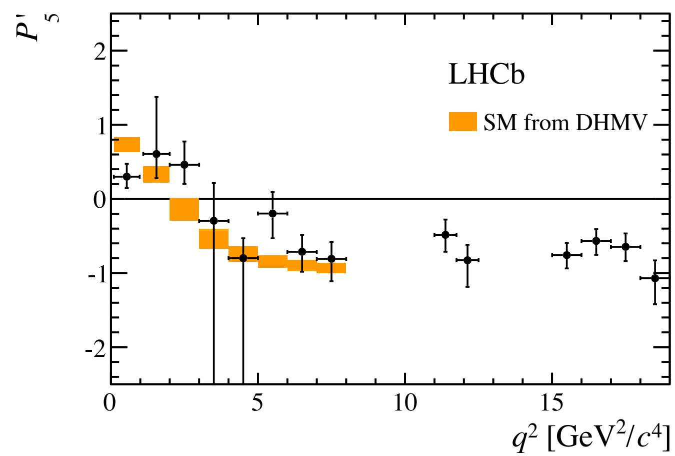
$$P_5' = \frac{J_5}{\sqrt{-J_{2c} J_{2s}}}\,, \quad J_5 = \sqrt{2} Re(A_0^L A_\perp^{L*})\,,$$

$$J_{2c} = -|A_0^L|^2\,, \quad J_{2s} = \frac{1}{4}\left(|A_\parallel^L|^2 + |A_\perp^L|^2\right)\,,$$

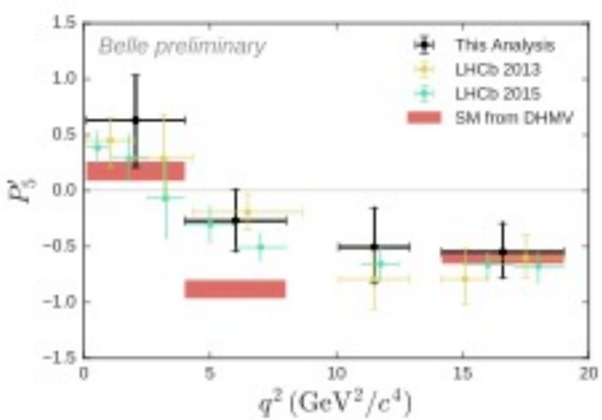
$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$
$$+ J_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_l \cos\phi + J_5 \sin 2\theta_K \sin\theta_l \cos\phi$$
$$+ (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7 \sin 2\theta_K \sin\theta_l \sin\phi + J_8 \sin 2\theta_K \sin 2\theta_l \sin\phi$$
$$+ J_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi\Big]\,, \qquad (2)$$



3.7σ deviations, LHCb, PRL111(13)



$\Delta ReC_9 = -1.04 \pm 0.25$ to fit the data, 3.4σdeviations, LHCb, JHEP1602(16)



2.1σ at Belle, arXiv: 1604.04042 [hep-ex]

- lepton non-universal couplings, $R_D, R_{D^*}, and\ R_K$

$$R_{D^{(*)}} = \frac{BR\left(B \to D^{(*)}\tau\nu\right)}{BR\left(B \to D^{(*)}\ell\nu\right)}$$

List of Observables			
Observable	Experimental Results		SM Prediction
	Experiment	Measured value	
R_D	Belle	$0.375 \pm 0.064 \pm 0.026$ [18]	0.299 ± 0.011 [19]
	BaBar	$0.440 \pm 0.058 \pm 0.042$ [20,21]	0.300 ± 0.008 [22]
	HFAG average	$0.397 \pm 0.040 \pm 0.028$ [17]	0.299 ± 0.003 [23] $\mathbf{0.300 \pm 0.011}$
R_{D^*}	Belle	$0.293 \pm 0.038 \pm 0.015$ [18]	
	Belle	$0.302 \pm 0.030 \pm 0.011$ [25]	
	BaBar	$0.332 \pm 0.024 \pm 0.018$ [20,21]	
	LHCb	$0.336 \pm 0.027 \pm 0.030$ [26]	0.252 ± 0.003 [24]
	HFAG average	$0.316 \pm 0.016 \pm 0.010$ [17]	$\mathbf{0.254 \pm 0.004}$
	Belle	$0.276 \pm 0.034\ ^{+0.029}_{-0.026}$ [27]	
	Our average	0.310 ± 0.017	

$$R_K = \left.\frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}\right|^{\text{exp}}_{q^2\in[1,6]\,\text{GeV}} = 0.745^{+0.090}_{-0.074} \pm 0.036\,.$$

2.6σ, LHCb, PRL113(14)

- Take these excesses seriously, we explain the anomalies with leptoquarks

Extension of the SM with leptoquarks (LQs):

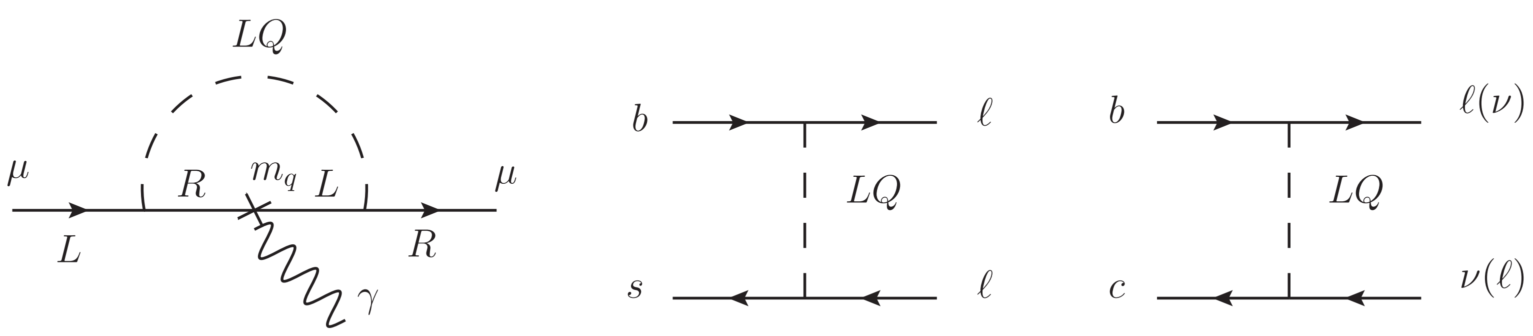
Properties of LQ:

(a) scalar (our case) or vector

(b) simultaneously couple to the SM quarks and leptons

(c) muon g-2 is from one-loop; $b \to s\, \ell^+ \ell^-$ and b $\to c\, \ell^- \nu$ are from tree

Sketched Feynman diagrams



- To get the top-quark enhancement for muon g-2, we consider a scalar doublet LQ; to smear the constraints from $B_s \to \mu^+\mu^-$, we also consider a scalar triplet LQ

- Charge assignment ($Q = I_3 + Y$):

For doublet LQ:

$$\bar{Q}_L \, \Phi_Y \, \ell_R : -\frac{1}{6} + Y - 1 = 0, Y = \frac{7}{6}$$

$$\bar{\ell}_L \, \Phi'_Y \, u_R \, (d_R): \frac{1}{2} + Y + \frac{2}{3}\left(-\frac{1}{3}\right) = 0, Y = -\frac{7}{6}\left(-\frac{1}{6}\right)$$

If we take $\Phi'_Y = i\sigma_2 \Phi^*_Y$, the LQ can couple to t_L and t_R; hence, the representaion for doublet LQ is :

$$\Phi_{7/6} = \begin{pmatrix} \phi^{\frac{5}{3}} \\ \phi^{\frac{2}{3}} \end{pmatrix}$$

For triplet LQ:

$$\bar{Q}^c{}_L i\tau_2 \Delta_Y\, \ell_L = Q_L^T C\, i\sigma_2\, \Delta_Y \ell_L:\ \frac{1}{6} + Y - \frac{1}{2} = 0, Y = \frac{1}{3}$$

the representaion for doublet LQ is :

$$\Delta_{1/3} = \begin{pmatrix} \delta^{1/3}/\sqrt{2} & \delta^{4/3} \\ \delta^{-2/3} & \delta^{1/3}/\sqrt{2} \end{pmatrix}$$

- Accordingly, the gauge invariant Yukawa couplings are given by

$$L_{LQ} = k_{ij}\bar{Q}_i \Phi_{7/6} \ell_{Rj} + \tilde{k}_{ij} \bar{L}_i \tilde{\Phi}_{7/6} u_{Rj} + y_{ij} \bar{Q}_i^c i\sigma_2 \Delta_{1/3} L_j + h.c.$$

$b \to c\ \ell\nu$

$g-2, \ell \to \ell'\gamma$

$$L_{LQ} = k_{ij}\left[\bar{u}_{Li}\,\ell_{Rj}\phi^{5/3} + \bar{d}_{Li}\,\ell_{Rj}\phi^{2/3}\right] + \tilde{k}_{ij}\left[\bar{\ell}_{Li}\,u_{Rj}\phi^{-5/3} - \bar{\nu}_{Li}\,u_{Rj}\phi^{-2/3}\right]$$
$$+ y_{ij}\left[\bar{u}^c_{Li}\,\nu_{Lj}\delta^{-2/3} - \frac{1}{\sqrt{2}}\bar{u}^c_{Li}\,\ell_{Lj}\delta^{1/3} - \frac{1}{\sqrt{2}}\bar{d}^c_{Li}\,\nu_{Lj}\delta^{1/3} - \bar{d}^c_{Li}\,\ell_{Lj}\delta^{4/3}\right] + h.c.$$

$b \to s\ \ell\ell$

$b \to c\ \ell\nu$

$b \to s\ \ell\ell$

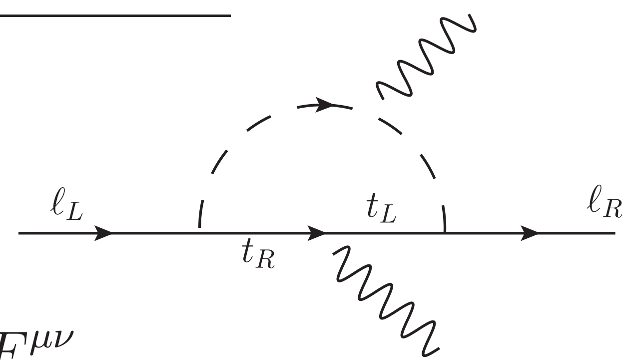
Phenomenological analysis:

❑ *Radiative lepton flavor violating processes*

❖ Current limits from $\ell_i \to \ell_j \gamma$ decays

Process	(i,j)	Experimental bounds (90% CL)
$\mu^- \to e^- \gamma$	$(2,1)$	$\mathrm{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13}$
$\tau^- \to e^- \gamma$	$(3,1)$	$\mathrm{BR}(\tau \to e\gamma) < 3.3 \times 10^{-8}$
$\tau^- \to \mu^- \gamma$	$(3,2)$	$\mathrm{BR}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$

❖ The effective interactions for $\ell_i \to \ell_j \gamma$



$$\mathcal{L}_{\ell_i \to \ell_j \gamma} = \frac{e}{2} \bar{\ell}_j \sigma_{\mu\nu} \left[(c_L)_{ji} P_L + (c_R)_{ji} P_R \right] \ell_i F^{\mu\nu}$$

❖ The Wilson coefficient of $(c_R)_{ji}$ is given by

enhanced factor

relevant couplings

$$(c_R)_{ji} \approx \frac{m_t}{(4\pi)^2}(k^\dagger)_{i3}\tilde{k}_{3j} \int d[X] \left(\frac{5}{\Delta(m_t, m_\Phi)} - \frac{2(1-x)}{\Delta(m_\Phi, m_t)} \right),$$

$$\Delta(m_1, m_2) = x m_1^2 + (y+z) m_2^2 \,,$$

$$\int [dX] = \int dx dy dz \delta(1-x-y-z) \,,$$

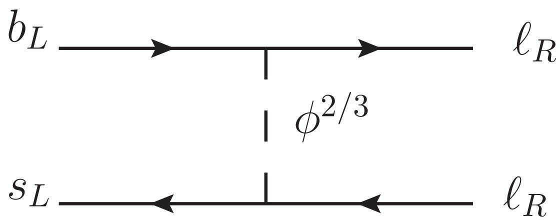
$(c_L)_{ji}$ can be obtained from $(c_R)_{ji}$ by exchanging k_{ab} *and* $\tilde{k}_{ab}$

❑ *Muon anomalous magnetic dipole moment,* muon g-2, can be related to $(c_R)_{\mu\mu}$ *and* $(c_L)_{\mu\mu}$ as

$$\Delta a_\mu \simeq -\frac{m_\mu}{2}(c_L + c_R)_{\mu\mu}$$

❑ $b \to s\, \ell^+ \ell^-$

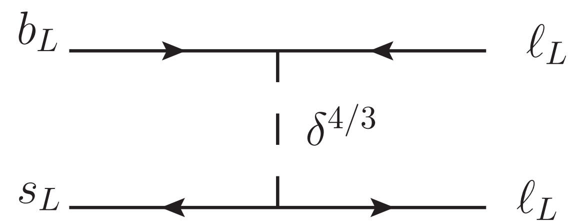
❖ from $\phi^{2/3}$



$$(S-P)\times(S+P) \xrightarrow{Fierz\ T.} (\mathrm{V}-\mathrm{A})\times(V+A)$$

$$H^1_{\text{eff}} = \frac{k_{b\ell}k_{s\ell}}{2m^2_\Phi}(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_R \ell)$$

❖ from $\delta^{4/3}$



$$(S-P)\times(S+P) \xrightarrow{Fierz\ T.} (\mathrm{V}-\mathrm{A})\times(V+A)^C$$
$$= -(V-A)\times(V-A)$$

$$H^2_{\text{eff}} = -\frac{y_{b\ell}y_{s\ell}}{2m^2_\Delta}(\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \ell)$$

❖ The effective Hamiltonian for $b \to s\, \ell\ell$

$$\mathcal{H} = \frac{G_F \alpha V_{tb}V^*_{ts}}{\sqrt{2}\pi}\left[H_{1\mu}\ell\gamma_\mu\ell + H_{2\mu}\bar{\ell}\gamma_\mu\gamma_5\ell\right]$$

$$H_{1\mu} = C^\ell_9 \bar{s}\gamma_\mu P_L b - \frac{2m_b}{q^2}C_7 \bar{s}i\sigma_{\mu\nu}q^\nu P_R b\,,$$

$$H_{2\mu} = C^\ell_{10}\bar{s}\gamma_\mu P_L b\,.$$

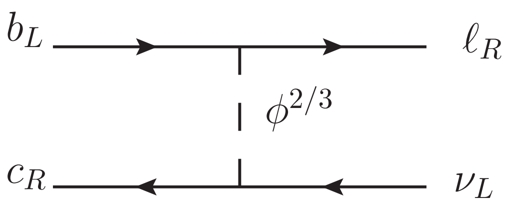
$$C^\ell_9 = C^{\text{SM}}_9 + C^{LQ,\ell}_9$$
$$C^\ell_{10} = C^{\text{SM}}_{10} + C^{LQ,\ell}_{10}$$

$$C^{LQ,\ell}_9 = -\frac{1}{c_{\text{SM}}}\left(\frac{k_{b\ell}k_{s\ell}}{4m^2_\Phi} - \frac{y_{b\ell}y_{s\ell}}{4m^2_\Delta}\right),$$
$$C^{LQ,\ell}_{10} = \frac{1}{c_{\text{SM}}}\left(\frac{k_{b\ell}k_{s\ell}}{4m^2_\Phi} + \frac{y_{b\ell}y_{s\ell}}{4m^2_\Delta}\right),$$

❖ enhancing $C_9^{LQ,\ell}$ and decreasing $\mathrm{C}_{10}^{\mathrm{LQ},\ell}$ can escape the constraint from $B_s \to \mu^+\mu^-$

❑ $b \to c\, \ell^- \nu$

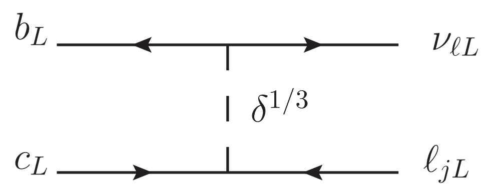
❖ from $\phi^{2/3}$



$$(S-P)\times(S-P) \xrightarrow{Fierz\ T.} (S-P)\times(S-P)$$
$$\frac{1}{4}\,\sigma^{\mu\nu}P_L \times \sigma_{\mu\nu}P_L$$

$$\mathcal{H} = \frac{k_{3j}\tilde{k}^*_{\ell 2}}{2m_\Phi^2}\Big(\bar{c}P_L b\bar{\ell}_j P_L \nu_\ell$$
$$+\frac{1}{4}\bar{c}\sigma^{\mu\nu}P_L b\bar{\ell}_j\sigma_{\mu\nu}P_L\nu_\ell\Big) + h.c.$$

❖ from $\delta^{1/3}$



$$(S-P)\times(S+P) \xrightarrow{Fierz\ T.} (V-A)\times(V+A)^C$$
$$= -(V-A)\times(V-A)$$

$$\mathcal{H} = -\frac{y_{3\ell}y^*_{2j}}{4m_\Delta^2}\left(\bar{c}\gamma_\mu P_L b\,\bar{\ell}_j\gamma^\mu P_L\nu_\ell\right) + h.c.$$

❖ $B \to D^{(*)}$ form factors

Melikhov & Stech, PRD62 (00)

$$\begin{aligned}
< P(M_2,p_2)|V_\mu(0)|P(M_1,p_1) > &= f_+(q^2)P_\mu + f_-(q^2)q_\mu, \\
< V(M_2,p_2,\epsilon)|V_\mu(0)|P(M_1,p_1) > &= 2g(q^2)\epsilon_{\mu\nu\alpha\beta}\epsilon^{*\nu}\,p_1^\alpha\,p_2^\beta, \\
< V(M_2,p_2,\epsilon)|A_\mu(0)|P(M_1,p_1) > &= i\epsilon^{*\alpha}\,[\,f(q^2)g_{\mu\alpha} + a_+(q^2)p_{1\alpha}P_\mu + a_-(q^2)p_{1\alpha}q_\mu\,], \\
< P(M_2,p_2)|T_{\mu\nu}(0)|P(M_1,p_1) > &= -2i\,s(q^2)\,(p_{1\mu}p_{2\nu} - p_{1\ nu}p_{2\mu}), \\
< V(M_2,p_2,\epsilon)|T_{\mu\nu}(0)|P(M_1,p_1) > &= i\epsilon^{*\alpha}\,[\,g_+(q^2)\epsilon_{\mu\nu\alpha\beta}P^\beta + g_-(q^2)\epsilon_{\mu\nu\alpha\beta}q^\beta + g_0(q^2)p_{1\alpha}\epsilon_{\mu\nu\beta\gamma}p_1^\beta p_2^\gamma\,],
\end{aligned}$$

$\varepsilon_{0123} = +1$

Numerical analysis:

- To explain the excess of angular observable P_5' in $B \to K^* \ell\ell$, we require $C_9^{LQ,\mu} \sim -1$, which is based on the global fitting,

Descotes-Genon etal, JHEP1606(16)

- $B_s \to \mu^+\mu^-$ constraint, $BR(B_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6})\times 10^{-9}$ LHCb-CMS

$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_s \to \mu^+\mu^-)^{\mathrm{SM}}} = \left|1 - 0.24 C_{10}^{LQ,\mu}\right|^2 \quad 0.21 < C_{10}^{LQ,\mu} < 0.79$$

Hiller, Schmaltz, PRD90(14)

- R_K is not sensitive to the $B \to K$ form factors, we use the result

$$0.7 \le Re(X^e - X^\mu) \le 1.5, \qquad \mathrm{X}^\ell = C_9^{LQ,\ell} - C_{10}^{LQ,\ell}$$

Hiller, Schmaltz, PRD90(14)

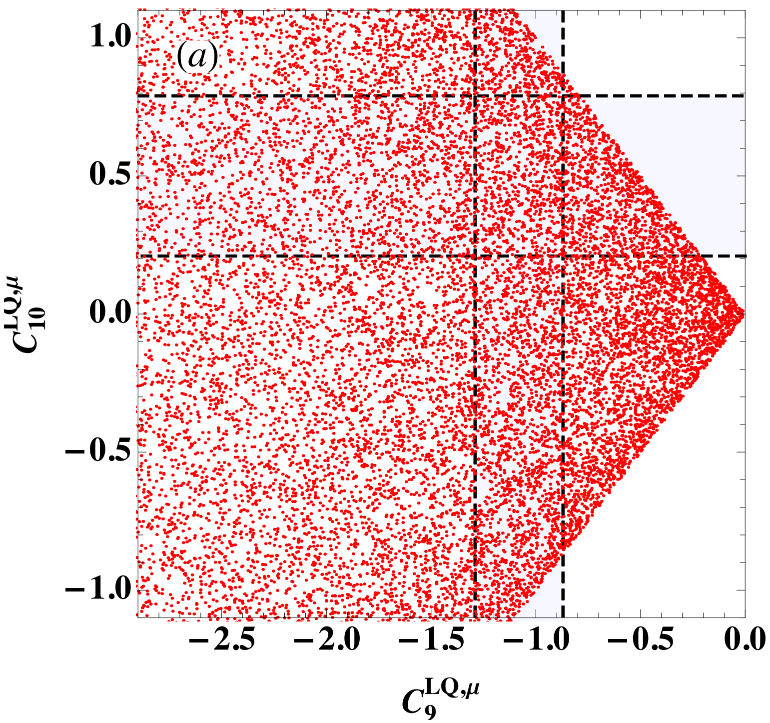
- Constraints from $\ell_i \to \ell_j \gamma$

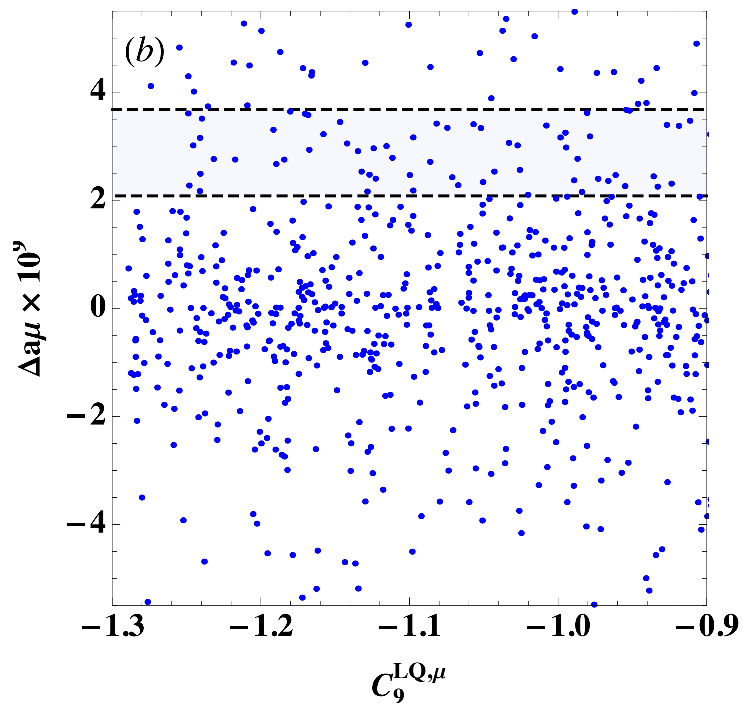
- The ranges of relevant parameters are set to be

$$m_{LQ} \in [700\,,1500\,]\ \mathrm{GeV}, \{k_{22}, \tilde{k}_{22}, y_{22}\} \in [-0.1\,,0.1]\,,$$
$$\{k_{33}, \tilde{k}_{33}, y_{33}\} \in [-0.01, 0.01]\,, \quad \{k_{23}, \tilde{k}_{23}, y_{23}\} \in [-0.1\,,0.1]\,,$$
$$k_{32} \in \mathrm{sign}(k_{22})[0, 0.5]\,, \quad \tilde{k}_{32} \in [-0.5\,,0.5]\,, \quad y_{32} \in -\mathrm{sign}(y_{22})[0\,,0.5]$$

- With the setting ranges of parameters, we scan the relevant parameter spaces

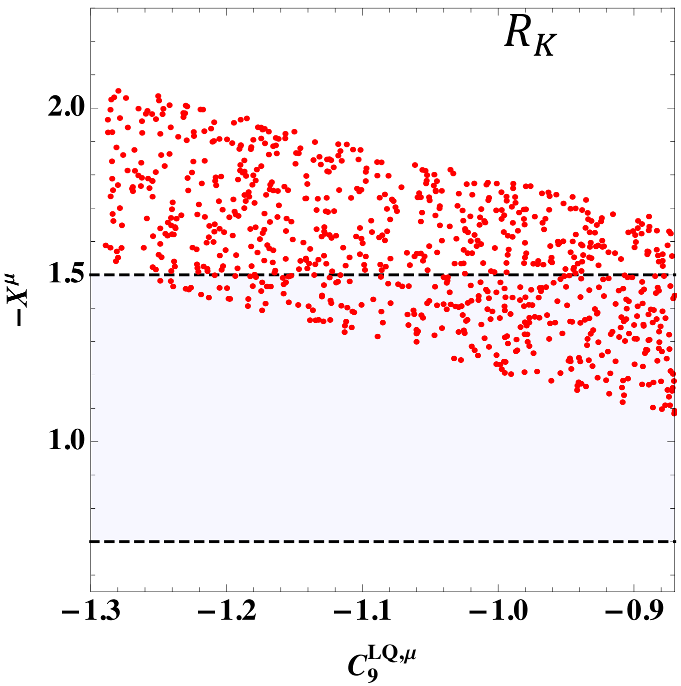
- correlation between $C_9^{LQ,\mu}$ and $C_{10}^{LQ,\mu}$ is given below figure (a)

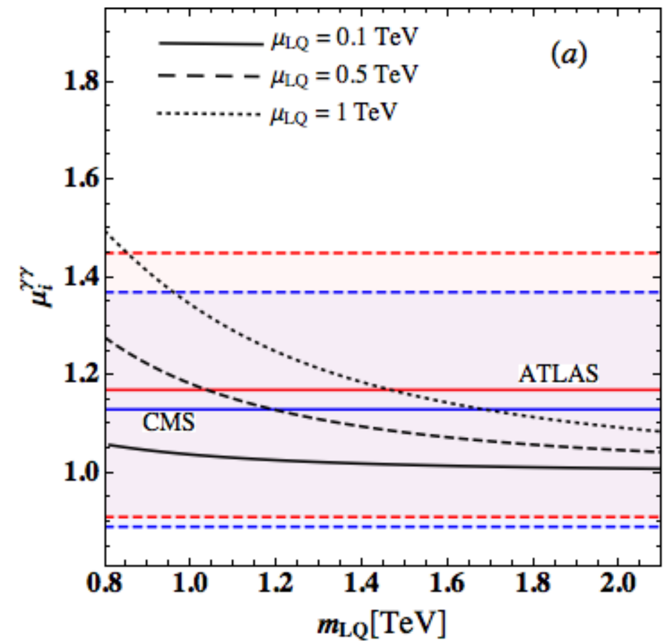




- correlation between Δa_μ and $C_9^{LQ,\mu}$ is given below figure (b)

- correlation between $X^{\ell} = C_9^{LQ,\ell} - C_{10}^{LQ,\ell}$ *and* $C_9^{LQ,\mu}$ is given below figure





- The SM Higgs can couple to the LQs through the scalar potential, the signal strength parameter $\mu^{\gamma\gamma}$ of Higgs to diphoton will be modified; By taking proper values of parameter, the contributions of LQ can fit the current LHC data

$$\mu_i^f = \frac{\sigma(pp \to h)}{\sigma(pp \to h)_{\rm SM}} \cdot \frac{{\rm BR}(h \to f)}{{\rm BR}(h \to f)_{\rm SM}} \equiv \mu_i \cdot \mu_f$$

Summary:

- Lepton non-universality is challenged in semileptonic B decays
- We study the resolution with leptoquarks, the excesses in $B \to K^{(*)}\ell^+\ell^-$ can be explained when the constraints from radiative leptons and $B_s \to \mu^+\mu^-$ are included
- The detailed analysis on R_D and R_{D^*} problem is in progress; More constraints from rare K, D and B decays need to further check