New physics models for $B \to K(K^*)l^+l^-$ anomalies and implications at the LHC and other experiments

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2017-05-11 "Anomalies in b to sll and its implications" @ University of Tokyo, Japan

Out line of the talk

1. Introduction
2. New physics models
3. Implications to experiments
4. Summary

□ Lepton universality in $b \to s l^+ l^-$: R_K, R_{K^*}

$$R_K \equiv \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$$

$$\left(R_K\right)^{SM} = 1, \quad \left(R_K\right)^{\exp} = 0.745 \pm 0.09 \pm 0.036$$

[R. Aaij et al [LHCb] PRL 113, 151601 (2017)]

~2.4 σ deviation from the SM

$$R_{K^*} \equiv \frac{BR(B \to K^* \mu^+ \mu^-)}{BR(B \to K^* e^+ e^-)}$$

$$\left(R_{K^*}\right)^{SM} = 1, \quad \left(R_K\right)^{\exp} = \begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.024 & (2m_\mu)^2 < q^2 < 1.1\, GeV^2 \\ 0.685^{+0.113}_{-0.069} \pm 0.047 & 1.1\, GeV^2 < q^2 < 6\, GeV^2 \end{cases}$$

[S. Bifani, CERN seminar, April 18 (2017)]

~2.4 σ deviation from the SM

Indicating lepton non-universality from new physics contribution

☐ Angular distribution in B→K*μ⁺μ⁻ (K*→Kπ)

[S. Descotes-Genon et al, JHEP 1301, 048 (2013); LHCb JHEP 1602, 104]

The deviation in angular distribution

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].$$

θ_K : between K & B in K* rest frame

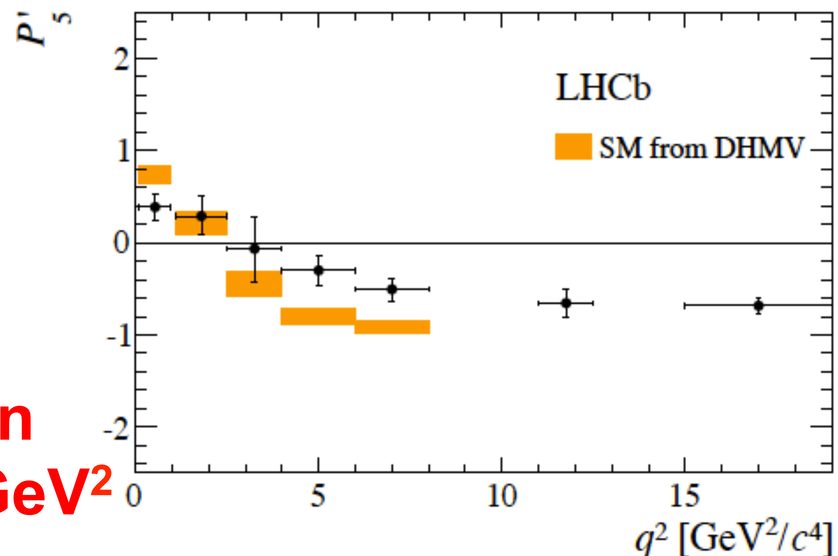
θ_l: between l and B in l+l- rest frame

Φ : between l+l- and Kπ decay plane

The P_5' is deviated from SM

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

~3σ deviation @q^2= 4~8 GeV^2



1. Introduction

✧ The relevant effective interaction terms

$$H^{l}_{eff} \supset -\frac{4G_F}{\sqrt{2}}\frac{e^2}{(4\pi)^2}V_{tb}V^*_{ts}$$
$$\times\left[C^l_9\left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{l}\gamma_\mu l\right)+\left(C^l_9\right)'\left(\bar{s}\gamma^\mu P_R b\right)\left(\bar{l}\gamma_\mu l\right)+C^l_{10}\left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{l}\gamma_\mu\gamma^5 l\right)+\left(C^l_{10}\right)'\left(\bar{s}\gamma^\mu P_R b\right)\left(\bar{l}\gamma_\mu\gamma^5 l\right)\right]$$

Or

$$H^{l}_{eff} \supset -\frac{4G_F}{\sqrt{2}}\frac{e^2}{(4\pi)^2}V_{tb}V^*_{ts}\sum_{X,Y=L,R}\left[C_{XY}\left(\bar{s}\gamma^\mu P_X b\right)\left(\bar{l}\gamma_\mu P_Y l\right)\right]$$

$\{C_9^{(')}, C_{10}^{(')}, C_{XY}\}$: Wilson coefficients

❖ Indication to BSM from global fit : $C_9^{\mu(BSM)} \sim -1, C_9^{\mu(BSM)} = -C_{10}^{\mu(BSM)} \sim -0.6 \Leftrightarrow C_{LL}^{\mu(BSM)} \sim -1$

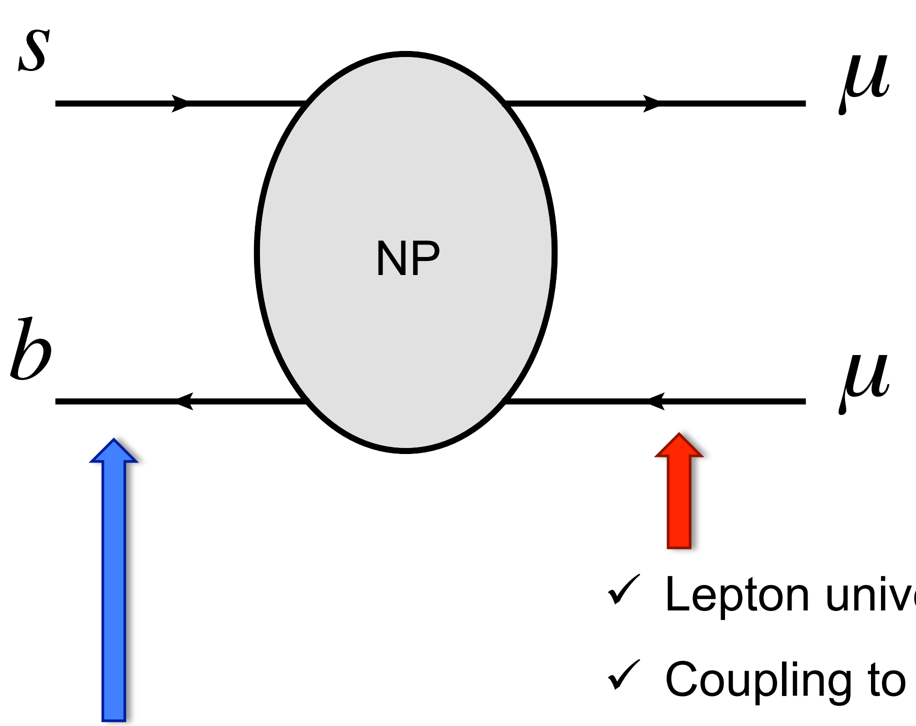
❖ Within 1-2 σ, data can be fitted with $C_{10}^{\mu(BSM)}\left(C_{LR}^{\mu(BSM)}\right) \sim 0$ [D'Amico et al, arxiv:1704.05438]

❖ R_K, R_{K^*} data can be fitted with Wilson coefficients for electron

➡ P_5' data prefer non-zero BSM contribution to Wilson coefficients for **muon**

New interaction with **muon** is also good to induce **muon** g-2

How the effective interactions can be induced from new physics?



$$\left|C_9^{\mu(BSM)}\right| \left(\left|C_{LL}^{\mu(BSM)}\right| \right) \sim 1$$

$$\left| \frac{4G_F}{\sqrt{2}} \frac{e^2}{(4\pi)^2} V_{tb} V_{ts}^* C_{9,LL}^{\mu(BSM)} \right| \sim \frac{0.003}{TeV^2}$$

- ✓ Lepton universality violation
- ✓ Coupling to μ would be larger than e

- ✓ Flavor changing b→s
- ✓ Left-handed b is preferred

Candidates of mediating particle

Z'

Leptoquark (LQ)

Extended Higgs sector

Vector-like quark (VLQ)

Etc.

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Types of new physics models

✧ Model with extended gauge symmetry

- ✓ Effective operator from Z’ exchange
- ✓ Extra U(1) symmetry with flavor dependent charge

✧ Models with leptoquarks

- ✓ Effective operator from LQ exchange
- ✓ Yukawa interaction with LQs provide flavor violation

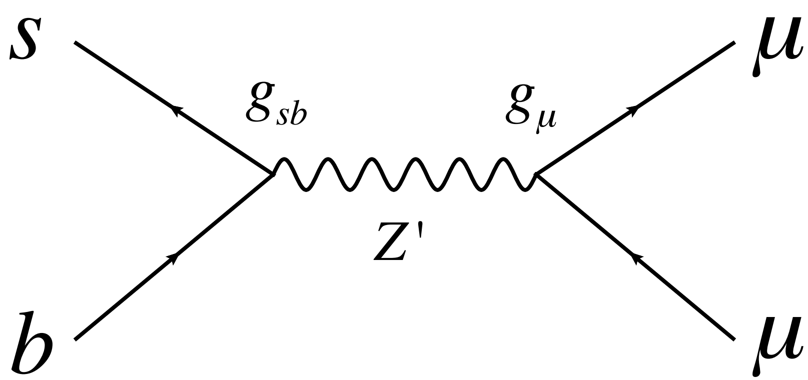
✧ Models with loop induced effective operator

- ✓ With extended Higgs sector and/or vector like quarks/leptons
- ✓ Flavor violation from new Yukawa interactions

There are other possibilities such as composite Higgs model etc.

✧ Model with extended gauge symmetry

The effective interactions can be induced via Z' exchange at tree level



$$C_9^{\mu(Z')} \approx \frac{\pi}{\sqrt{2} V_{tb} V_{ts}^{*} \alpha G_F} \frac{g_{sb} g_{\mu}}{m_{Z'}^2}$$

✓ Flavor violating coupling in quark sector

- SM quarks have flavor dependent charge under extra local U(1)
- SM quarks mix with exotic quark with local U(1) charge
- Loop induced Z'qq' interaction via exotic particles

✓ Lepton flavor non-universality

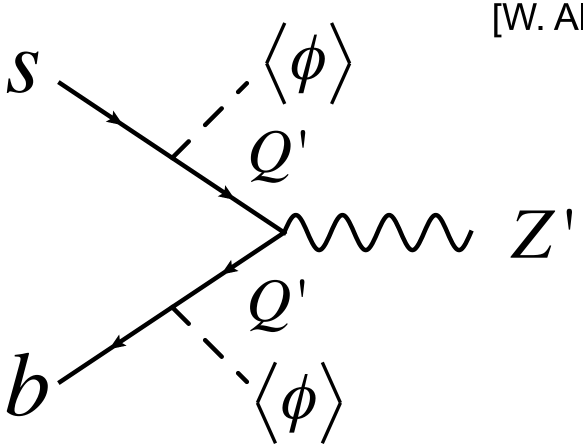
- $U(1)_{\mu-\tau}$ (-like) gauge symmetry works

- **Let us discuss some examples of extra U(1) models**

2. New physics models

- **$U(1)_{\mu\text{-}\tau}$ (-like) symmetry with quark – vector like quark mixing**

[W. Altmannshofer, S. Gori, M. Pospelov, I. Yavin, PRD 89, 095033 (2014)]



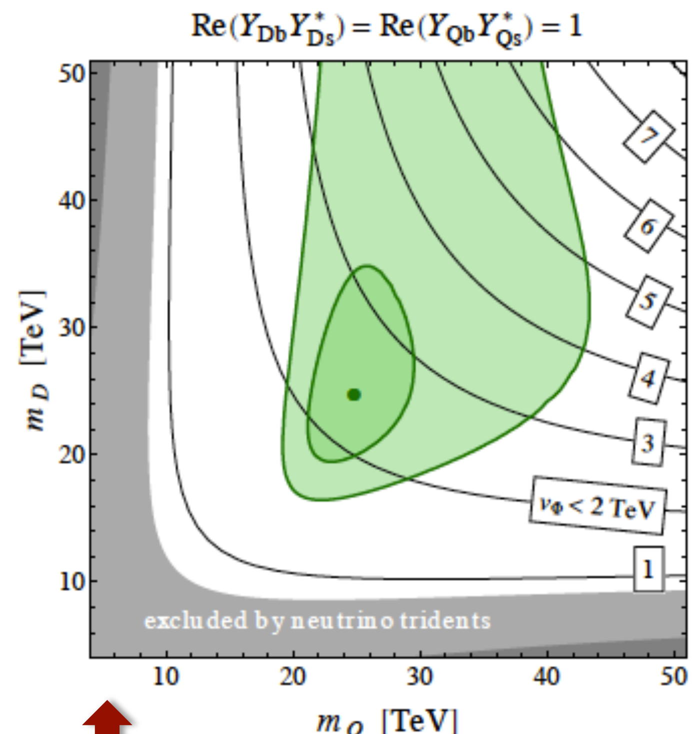
- ✓ Q' is VLQs with extra U(1) charge
- ✓ Φ is some extra scalar field
- ✓ Quark coupling from the mixing effect
- ✓ Z' couples to μ at tree level

VLQs

$$Q_L = (\mathbf{3},\mathbf{2})_{+1/6,+1}\ ,\quad \tilde{Q}_R = (\mathbf{3},\mathbf{2})_{+1/6,+1}\ ,$$
$$\tilde{D}_L = (\mathbf{3},\mathbf{1})_{-1/3,-1}\ ,\quad D_R = (\mathbf{3},\mathbf{1})_{-1/3,-1}\ ,$$
$$\tilde{U}_L = (\mathbf{3},\mathbf{1})_{+2/3,-1}\ ,\quad U_R = (\mathbf{3},\mathbf{1})_{+2/3,-1}\ ,$$

Yukawa terms for mixing

$$\begin{aligned}\mathcal{L}_{\rm mix} = \ & \Phi \bar{\tilde{D}}_R (Y_{Qb} b_L + Y_{Qs} s_L + Y_{Qd} d_L) \\ & + \Phi \bar{\tilde{U}}_R (Y_{Qt} t_L + Y_{Qc} c_L + Y_{Qu} u_L) \\ & + \Phi^\dagger \bar{\tilde{U}}_L (Y_{Ut} t_R + Y_{Uc} c_R + Y_{Uu} u_R) \\ & + \Phi^\dagger \bar{\tilde{D}}_L (Y_{Db} b_R + Y_{Ds} s_R + Y_{Dd} d_R) \ + \ \text{h.c.}\end{aligned}$$



B_s mixing constraint is imposed

➢ $U(1)_{\mu-\tau}$ (-like) symmetry with quark – vector like quark mixing

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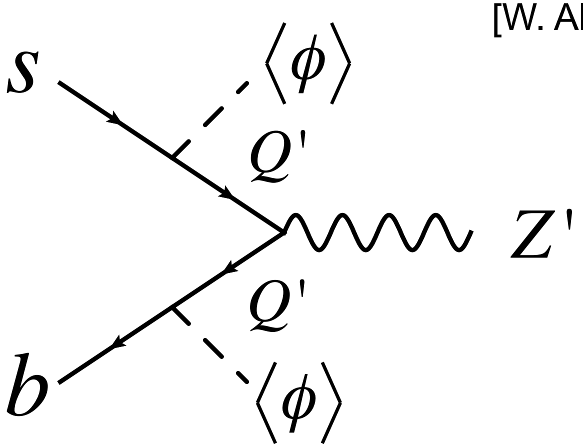

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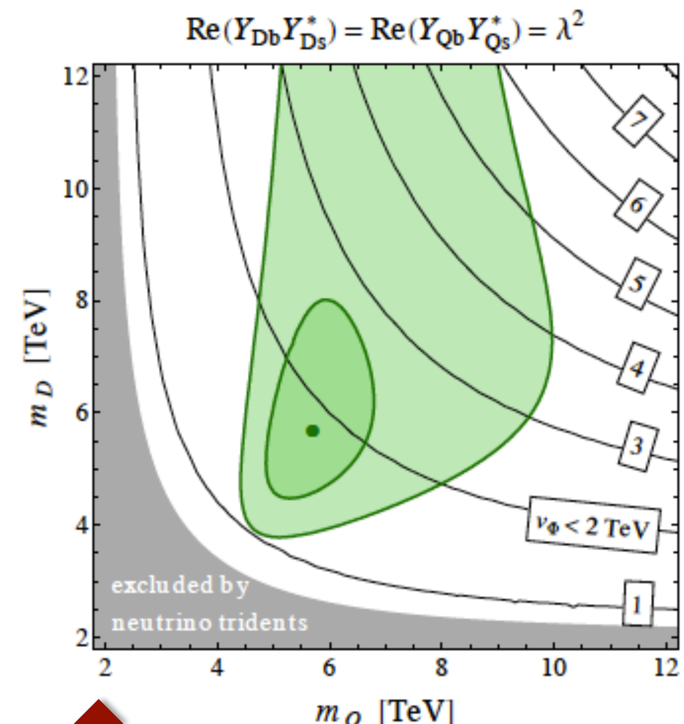


B_s mixing constraint is imposed

2. New physics models

- **Flavor dependent U(1) model: $U(1)_{\mu-\tau-a(B1+B2-2B3)}$**

[A. Crivellin, G. D'Ambrosio, J. Heeck, PRD 91, 075006 (2015)]

$$\{Q_L^{1,2}, u_R^{1,2}, d_R^{1,2}\} : Q_X = -\frac{a}{3}, \quad \{Q_L^3, u_R^3, d_R^3\} : Q_X = \frac{2a}{3}$$

$$\{L_L^2, e_R^2, \nu_R^2\} : Q_X = 1, \quad \{L_L^3, e_R^3, \nu_R^3\} : Q_X = -1$$

$$\Phi_2 : Q_X = -\frac{a}{3}$$

- ✓ 2HDM with the extra U(1)
- ✓ Extension of $U(1)_{\mu-\tau}$
- ✓ Φ_2 for getting CKM matrix

Quark Yukawa couplings :

$$-L_Y = \bar{Q}_f \left(\xi_{fi}^u \tilde{\Phi}_1 + Y_{fi}^u \tilde{\Phi}_2\right) u_i + \bar{Q}_f \left(\xi_{fi}^d \Phi_1 + Y_{fi}^d \Phi_2\right) d_i + h.c.$$

Flavor violating quark coupling with CKM matrix

$$g' \bar{d}_i \gamma^\mu P_L d_j Z'_\mu (V_{CKM}^* Q V_{CKM})_{ij}$$
$$Q = diag\{-a/3, -a/3, 2a/3\}$$

$$\Rightarrow \quad C_9^{\mu(Z')} \approx \frac{-a g_X^2}{\sqrt{2} m_{Z'}^2} \frac{\pi}{\alpha G_F} \approx -\left(\frac{a}{1/3}\right)\left(\frac{3\,TeV}{m_{Z'}/g_X}\right)^2$$

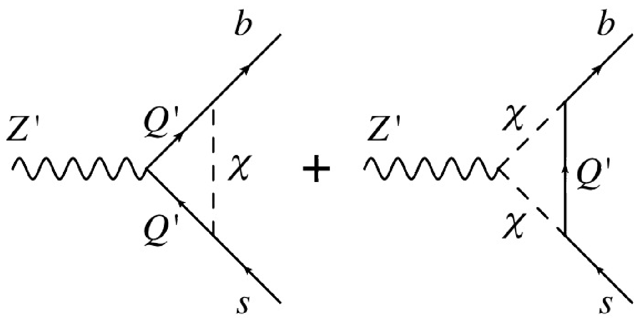
- C_9 ~ -1 BSM contribution can be obtained with TeV scale Z'
- Z' contribution to other Wilson coefficients is small
- Flavor violation in Yukawa coupling sector

➢ Loop induced interaction in $U(1)_{\mu-\tau}$ (-like) gauge symmetry

[P. Ko, TN, H. Okada, arXiv: 1702.02699]

	VLQ Q'_a	Scalar χ
$SU(3)_C$	3	1
$SU(2)_L$	2	1
$U(1)_Y$	$\frac{1}{6}$	0
$U(1)_{\mu-\tau}$	q_x	q_x

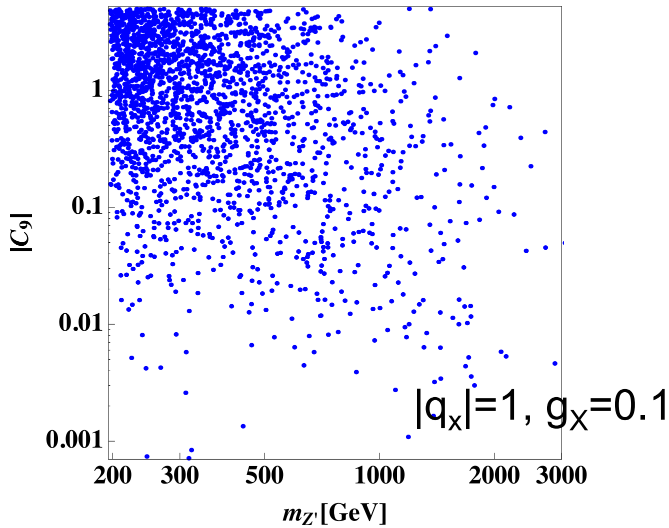
Exotic Z_2 odd particles



Z'-b-s coupling via loop effect

$$-L \supset f_{aj}\bar{Q}'_a P_L Q_j \chi + h.c.$$: Yukawa coupling

$$C_9^{\mu(Z')} \approx \frac{\sqrt{2}\pi}{V_{tb}V_{ts}^*\alpha G_F}\frac{q_x g_X^2}{m_{Z'}^2} f_{3a}^* f_{a2} F_{loop}$$



✧ Singlet scalar χ can be DM candidate

➢ There are also other models based on Z' interaction

✧ Models with leptoquarks

Leptoquark : particles couples with leptons and quarks

Some example of scalar leptoquarks to induce relevant H_{eff}

- $SU(2)_L$ singlet S: (3, 1, 1/3) [(SU(3),$SU(2)_L$,$U(1)_Y$)]

$$-L \supset \left[x_{ij} \bar{Q}_i^c P_L L_j + y_{ij} \bar{u}_i^c P_R e_j \right] S + h.c.$$

- $SU(2)_L$ doublet Φ: (3, 2, 7/6)

$$-L \supset k_{ij} \bar{Q}_i P_R e_j \Phi + g_{ij} \bar{L}_i P_R u_j (i\sigma_2) \Phi^* + h.c. \qquad \Phi = \begin{pmatrix} \phi_{5/3} \\ \phi_{2/3} \end{pmatrix}$$

- $SU(2)_L$ triplet Δ: (3, 3, 1/3)

$$-L \supset w_{ij} \bar{Q}_i^c P_L L_j \Delta + h.c. \qquad \Delta = \begin{pmatrix} \delta_{1/3}/\sqrt{2} & \delta_{4/3} \\ \delta_{-2/3} & -\delta_{1/3}/\sqrt{2} \end{pmatrix}$$

Vector leptoquarks can be also applied

Ex) [R. Barbieri, C.W. Murphy, F. Senia, EPJC77, 8 (2016);
S. Sahoo, R. Mohanta, A.K. Giri, PRD95, 035027 (2017); etc.]

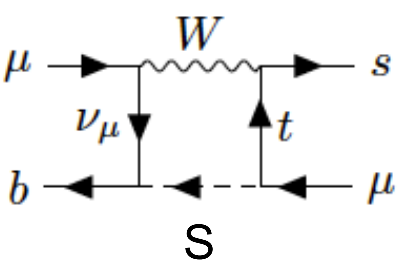
● Model with $SU(2)_L$ singlet S: (3, 1, 1/3)

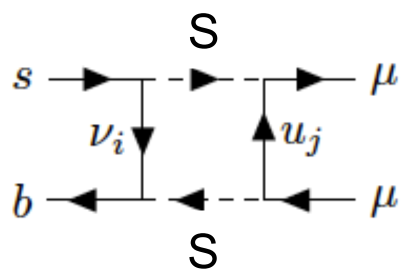
[M. Bauer, M. Neubert, PRL116, 141802 (2016); Y. Cai et al, arXiv: 1704.05849]

$$-L \supset \left[x_{ij} \bar{Q}_i^c P_L L_j + y_{ij} \bar{u}_i^c P_R e_j \right] S + h.c.$$

$$\Rightarrow \left[(V_{CKM}^* x)_{ij} \bar{u}_i^c P_L e_j - x_{ij} \bar{d}_i^c P_L \nu_j + y_{ij} \bar{u}_i^c P_R e_j \right] S + h.c.$$

Contribution to C_{LL}, C_{LR} at one-loop level





$$C_{LL}^{\mu(LQ)} = \frac{m_t^2}{8\pi\alpha m_S^2} \left| \left(V_{CKM}^* x \right)_{23} \right|^2 - \frac{\sqrt{2}}{64\pi\alpha G_F m_S^2 V_{tb} V_{ts}^*} \left(x_{i3} x_{i2}^* \right) \left| z_{2j} \right|^2$$

$$C_{LR}^{\mu(LQ)} = \frac{m_t^2}{8\pi\alpha m_S^2} \left| y_{23} \right|^2 F_{loop}(m_t, m_W, m_S) - \frac{\sqrt{2}}{64\pi\alpha G_F m_S^2 V_{tb} V_{ts}^*} \left(x_{i3} x_{i2}^* \right) \left| y_{2j} \right|^2$$

- ❖ Constraints from B→Kνν
- ❖ C_{LL} ~ - 0.6 at most; bit small to explain the R_K, R_{K^*}
- ❖ It can explain R_D, R_{D^*} anomaly

2. New physics models

- **Model with $SU(2)_L$ doublet Φ: (3, 2, 7/6)**

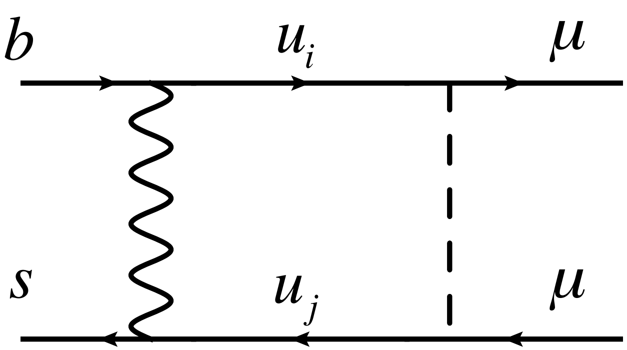
[D. Becirevic, O. Sumensari, arXiv: 1704.05835]

$$-L \supset k_{ij}\bar{Q}_i P_R e_j \Phi + g_{ij}\bar{L}_i P_R u_j (i\sigma_2)\Phi^* + h.c.$$

$$\Rightarrow (V_{CKM}k)_{ij}\bar{u}_i P_R e_j \phi_{5/3} + k_{ij}\bar{d}_i P_R e_j \phi_{2/3} - g_{ij}\bar{e}_i P_R u_j \phi_{-5/3} + g_{ij}\bar{\nu}_i P_R u_j \phi_{-2/3}$$

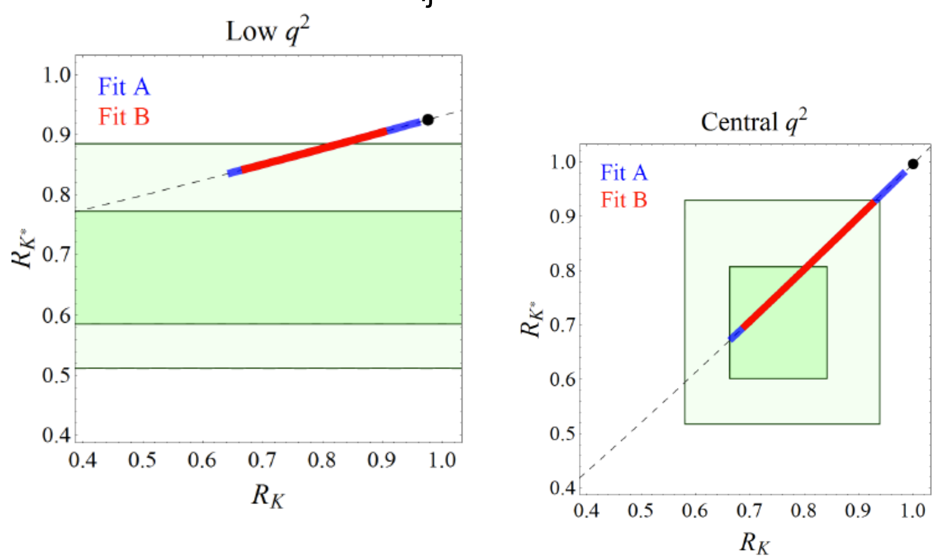
✓ Interaction with k_{ij} contribute to C_{LR} at tree level

✓ Interaction with g_{ij} contribute to C_{LL} at one-loop level



$$C_{LL}^{\mu(LQ)} \propto \frac{V_{u_i b} V_{u_j s}^*}{V_{tb} V_{ts}^*} g_{i2} g_{j2}^* I_{loop}$$

Fitting with k_{ij}=0



2. New physics models

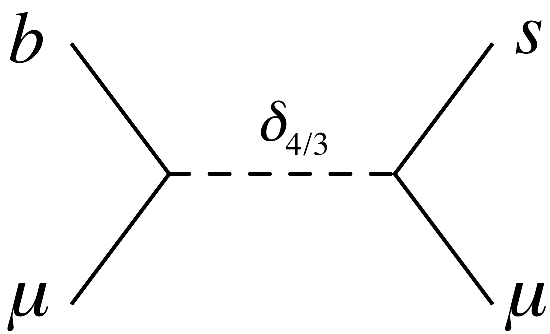
● Model with SU(2)$_L$ triplet Δ: (3, 3, 1/3)

[C. Chen, TN, H. Okada, PRD 94, 115005 (2016)]

$$-L \supset w_{ij}\bar{Q}^c_i P_L L_j \Delta + h.c.$$

$$\Rightarrow (V^*_{CKM} w)_{ij}\bar{u}^c_i P_L \nu_j \delta_{-2/3} - \frac{1}{\sqrt{2}}(V^*_{CKM} w)_{ij}\bar{u}^c_i P_L e_j \delta_{1/3} - \frac{1}{\sqrt{2}} w_{ij}\bar{d}^c_i P_L \nu_j \delta_{1/3} - w_{ij}\bar{d}^c_i P_L e_j \delta_{4/3}$$

✓ Contribution to C$_{LL}$ at tree level



$$C^{\mu(LQ)}_{LL} = \frac{\sqrt{2}\pi}{4V_{tb}V^*_{ts}\alpha G_F}\frac{w_{32}w_{22}}{m^2_\Delta}$$

$$\approx -\frac{w_{32}w_{22}}{0.003}\left(\frac{TeV}{m_\Delta}\right)^2$$

❖ C$_{LL}$ ~ -1 can be obtained with small Yukawa for O(1) TeV LQ

❖ C$_{LR}$ = 0 at tree level

❖ Δ can be applied to radiative neutrino model adding other LQs

[K. Cheung, TN, H. Okada, PRD 94, 115018 (2016); PRD 95, 015026 (2017); PLB768, 359 (2017)]

✧ Models with loop induced effective operator

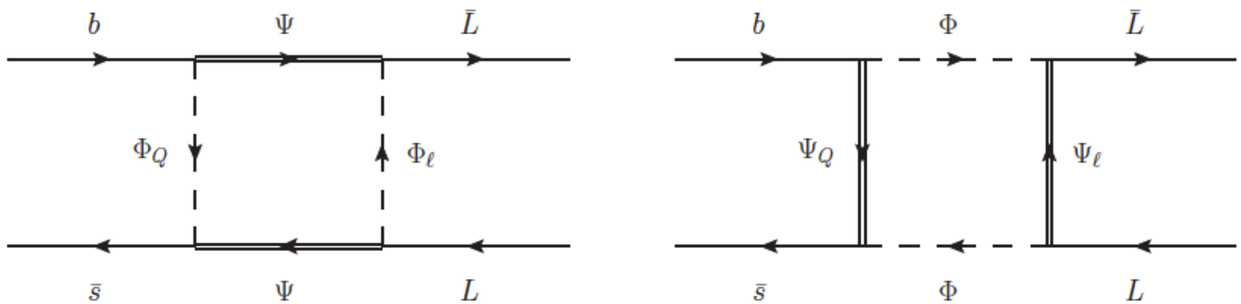
[P. Arnan et al, JHEP 1704, 043 (2017)]

✓ Adding some VLQs Ψ and exotic scalars Φ

$$\mathcal{L}_{\rm int}^{a)} = \Gamma_i^Q \bar{Q}_i P_R \Psi \Phi_Q + \Gamma_i^L \bar{L}_i P_R \Psi \Phi_\ell + \text{h.c.}.$$

$$\mathcal{L}_{\rm int}^{b)} = \Gamma_i^Q \bar{Q}_i P_R \Psi_Q \Phi + \Gamma_i^L \bar{L}_i P_R \Psi_\ell \Phi + \text{h.c.}.$$

✓ Box diagrams induce relevant operator for b→sll



a) b)

$$C_9^{\text{box}, a)} = -C_{10}^{\text{box}, a)} = \mathcal{N} \frac{\Gamma_s \Gamma_b^* |\Gamma_\mu|^2}{32\pi \alpha_{\rm EM} m_\Psi^2} \left(\chi \eta F(x_Q, x_\ell) + 2\chi^{\rm M} \eta^{\rm M} G(x_Q, x_\ell) \right),$$

$$C_9^{\text{box}, b)} = -C_{10}^{\text{box}, b)} = -\mathcal{N} \frac{\Gamma_s \Gamma_b^* |\Gamma_\mu|^2}{32\pi \alpha_{\rm EM} m_\Phi^2} \left(\chi \eta - \chi^{\rm M} \eta^{\rm M} \right) F(y_Q, y_\ell),$$

❖ O(1) Yukawa coupling is required to fit R_K, R_{K^*}

❖ B→Kνν is also affected: constraint should be imposed

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3. Implications to experiments

New physics Models would have some exotic particles

- ✓ Z' boson which is flavor dependence
- ✓ Leptoquarks
- ✓ Vector like quarks and/or extended Higgs

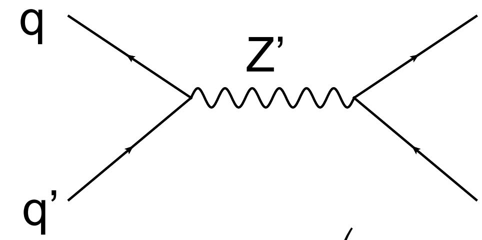
Some implications to experiments from these new particels

- ❖ Direct production at the LHC
- ❖ Exotic particle exchanging processes at the LHC
- ❖ New physics effect to B decay (other than $B \to K l^+ l^-$)
- ❖ Flavor violating processes

✧ Signature of new physics at the LHC

✓ Z' production

$$L \supset \left[g_{bs} \left(\bar{s}\gamma^{\mu} P_L b + h.c. \right) + g_{\mu} \bar{\mu}\gamma^{\mu}\mu \right] Z'_{\mu}$$



$$\Rightarrow \quad C_9^{\mu(Z')} \sim -1 \Rightarrow |g_{\mu} g_{bs}| \sim 0.008 \times \left(\frac{m_{Z'}}{1000GeV} \right)^2$$

Z' can be produced at the LHC (13 TeV)

Production cross section for some benchmark points; $m_{Z'}$ = 1000 GeV

① $\{g_{\mu}, g_{qq'}\}=\{0.8, 0.01\}$: $\sigma_{pp\to Z'} \sim 0.1$ pb

② $\{g_{\mu}, g_{bb,bs,ss,cc}\}=\{0.8, 0.01\}$: $\sigma_{pp\to Z'} \sim 1.0\times10^{-3}$ pb

} $\mu^+\mu^-$ signal

③ $\{g_{\mu}, g_{bb,bs,ss,cc}\}=\{0.02, 0.4\}$: $\sigma_{pp\to Z'} \sim 1.6$ pb

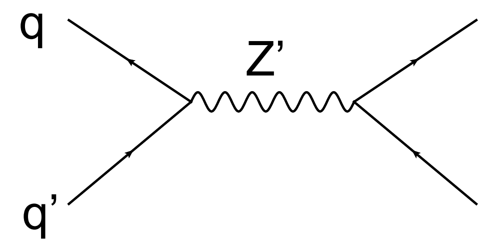
di-jet signal

② : safe from experimental constraints
①, ③ : excluded

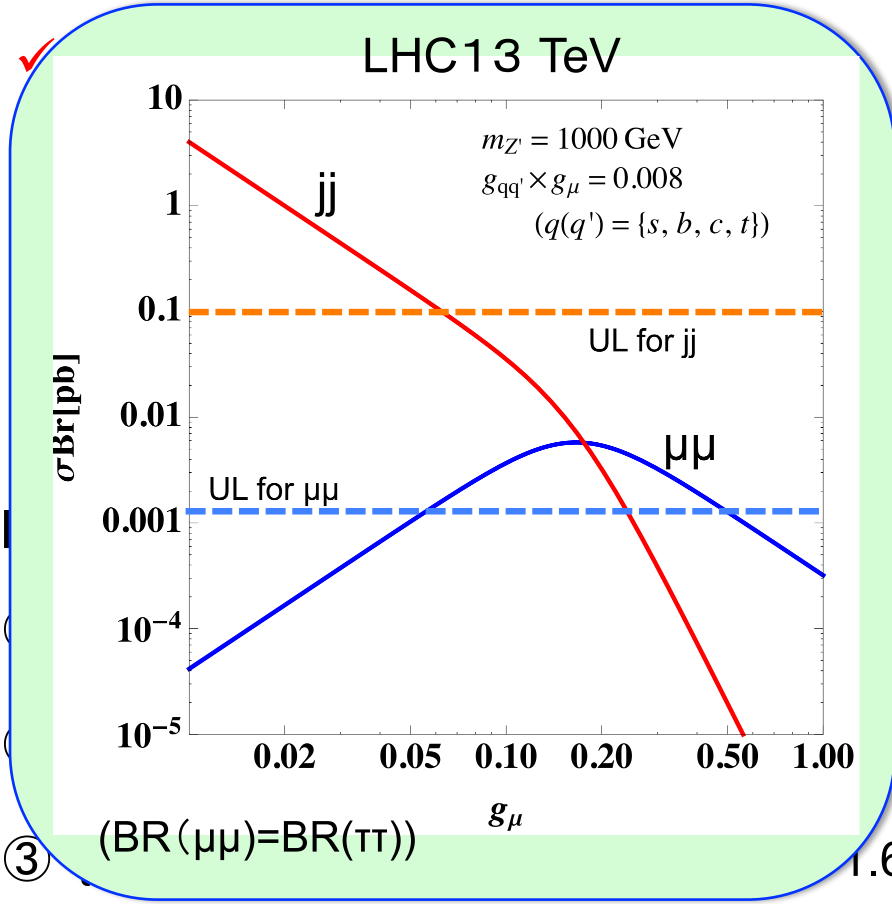
⇒ More parameter region will be tested with more integrated luminosity

[ATLAS-CONF-2016-045, CMS-PAS-EXO-16-031, ATLAS-CONF-2016-069]

✧ Signature of new physics at the LHC



$$C_9^{\mu(Z')} \sim -1 \Rightarrow \left|g_\mu g_{bs}\right| \sim 0.008 \times \left(\frac{m_{Z'}}{1000GeV}\right)^2$$



3 TeV)

nchmark points; $m_{Z'}$ = 1000 GeV

0×10^{-3} pb

μ+μ- signal

③ .6 pb

di-jet signal

② : safe from experimental constraints

①, ③ : excluded

More parameter region will be tested with more integrated luminosity

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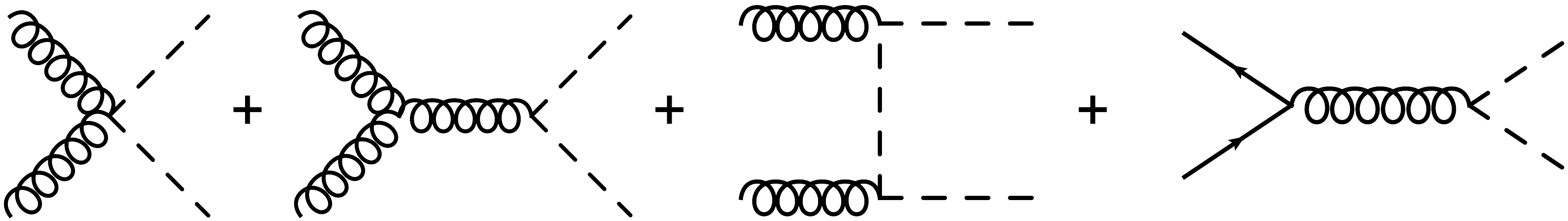
✧ Signature of new physics at the LHC

✓ LQ production

LQs can be produced via QCD processes at the LHC



The production cross section is sizable

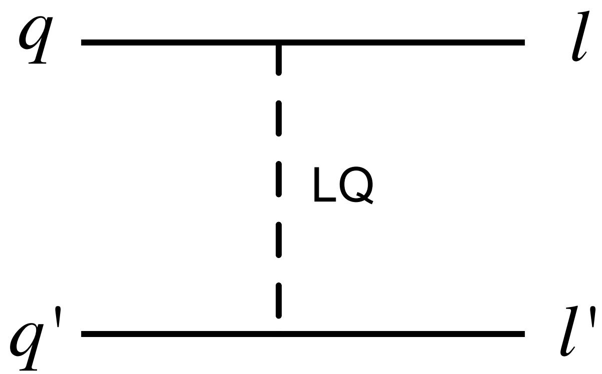
- $\sigma_{pp\to LQLQ}$ ~ few×10 fb for m_{LQ} = 1 TeV

- LQs decays into quarks + leptons
- BRs of LQ depend on Yukawa coupling
- Model structure would be tested by measuring BRs

✧ Signature of new physics at the LHC

✓ LQ mediating process in t-channel

LQs contribute to pp→ll process by t-channel exchange



- ✓ It depends on Yukawa coupling
- ✓ Indirect signal of leptoquark
- ✓ Affect to angular distribution of leptons

✓ Other VLQs and/or exotic scalar production

- ❖ Some models include VLQs and/or exotic scalars
- ❖ They are also expected to be produced at the LHC
- ❖ Signals depend on structure of models

✧ Implications to other rare B decays

BSM for explaining $b \to s l^+ l^-$ anomalies also affect other B decays

✓ $B_s \to \mu^+ \mu^-$

Effective operator contributing the process: $\left(\bar{s}\gamma^{\mu} P_{L(R)} b\right)\left(\bar{\mu}\gamma_{\mu}\gamma^{5} l\right)$

➡ Corresponding to C_{10}, C_{10}' (or C_{LL})

$$BR(B_s \to \mu^+\mu^-) \approx \left|1 - 0.24 C_{10}^{\mu(BSM)} + 0.23 C_{10}^{\mu(BSM)\prime}\right| BR(B_s \to \mu^+\mu^-)_{SM}$$

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

$$BR(B_s \to \mu^+\mu^-)_{\exp} \approx (3.0 \pm 0.6) \times 10^{-9}$$

[LHCb, arXiv : 1703.05747]

Ex) $C_9^{\mu(BSM)} = -C_{10}^{\mu(BSM)} = -1 \; (C_{LL}^{\mu(BSM)} = -1)$

$$\Rightarrow \quad 2.6 \times 10^{-9} \leq BR(B_s \to \mu^+\mu^-) \leq 2.9 \times 10^{-9}$$

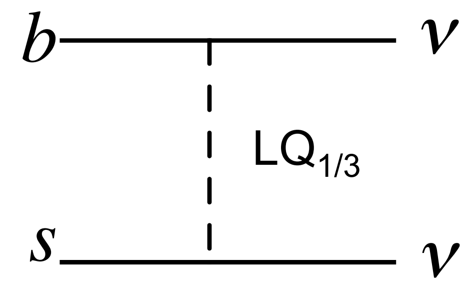
Measurement of the deviation from SM is expected

3. Implications to experiments

✓ **$B^+ \to K^+\nu\nu$**

Some leptoquarks contribute to the process

Ex) SU(2) singlet and triplet leptoquarks



$$BR(B^+ \to K^+\nu\nu) \approx \frac{1}{3}\left(\sum_l |1-r_l|^2\right) BR(B^+ \to K^+\nu\nu)_{SM}$$

$$|r_l| \sim 400 \times \frac{TeV^2}{2m_S^2} y_{3l} y_{2l} \left[\frac{TeV^2}{4m_\Delta^2} w_{3l} w_{2l}\right]$$ For singlet [triplet]

Upper limit by experiment and SM prediction

$$BR(B^+ \to K^+\nu\nu) < 1.6 \times 10^{-5}, \quad BR(B^+ \to K^+\nu\nu)_{SM} \approx 5 \times 10^{-6}$$

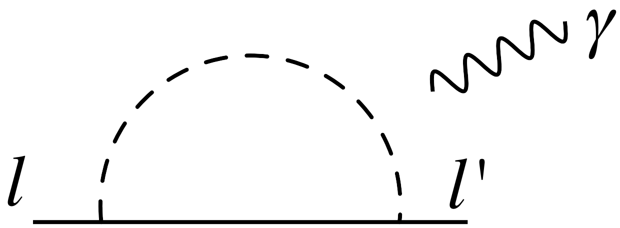
- ❖ Roughly we have $|1-r_l| < 3$
- ❖ Triplet case is less significant since $|w_{32}w_{22}| \sim 0.003 \times (m_\Delta/TeV)^2$ for R_K, R_{K^*}
- ❖ Stringent constraint for singlet LQ model

→ ~20% change from SM

3. Implications to experiments

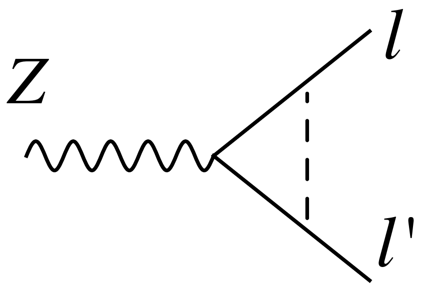
LQs and VLQs can also contribute to LFV processes

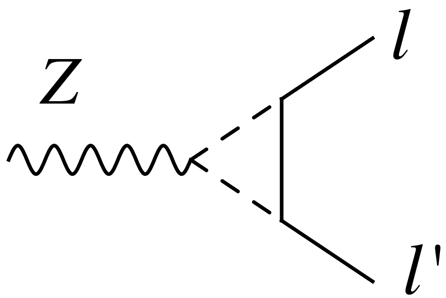
- ✓ **LFV radiative lepton decay l→l'γ**



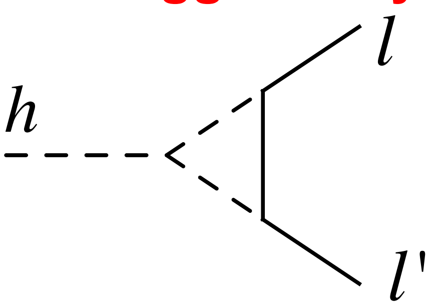
- ✓ Strong constraint from μ→eγ
- ✓ It also contributes to muon g-2
- ✓ Doublet LQ would give large contribution

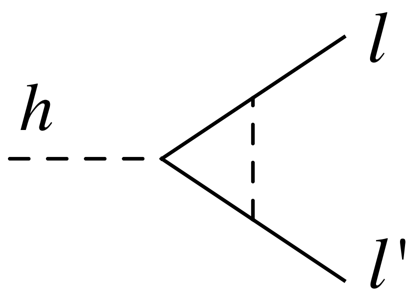
- ✓ **LFV Z decay Z→l'l**





- ✓ **LFV SM Higgs decay h→l'l**





If exotic particles interact with charged leptons other than μ

□ Prospect in experiments

◆Z' boson

- ✓ Di-muon signal is expected
- ✓ Clear signal in the LHC
- ✓ Di-jet or top quark pair productions are also expected

◆LQs, VLQs, extended Higgs

- ✓ They could be produced at the LHC
- ✓ Signals depend on the structure of new physics models
- ✓ Contributions to other rare B decay and LFV processes

  → they would be tested by Belle II, LHCb etc.

Summary and Discussions

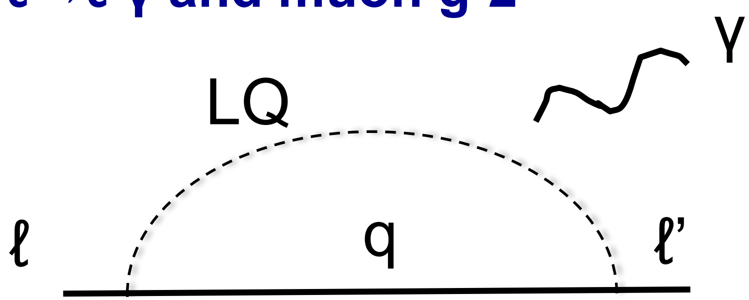
- Models for explaining $b \to s l^+ l^-$ anomalies are reviewed
  - ✓ Models with Z' boson
  - ✓ Leptoquark models
  - ✓ Loop induced operator model
- Some implications to signals in experiments are discussed
  - ✓ Signals at the LHC
  - ✓ Implications to other rare B decays
  - ✓ Lepton flavor violation processes

Thanks for listening !

Appendix

LFV and muon g-2 from SU(2) doublet leptoquark

- **$\ell \to \ell' \gamma$ and muon g-2**



: diagram for LFV and muon g-2

$$L_{eff} = \frac{e}{2} \bar{\ell}_j \sigma_{\mu\nu} [(c_L)_{ji} P_L + (c_R)_{ji} P_R] \ell_i F^{\mu\nu}$$

$$(c_R)_{ji} \approx \frac{m_t}{(4\pi)^2} (k^T)_{i3} g_{3j} \int dx\, dy\, dz\, \delta(1-x-y-x) \left(\frac{5}{x m_t^2 + (y+z) m_\Phi^2} - \frac{2(1-x)}{x m_\Phi^2 + (y+z) m_t^2} \right), \quad k \leftrightarrow g \text{ for } C_L$$

Branching fraction and g-2

$$BR(\ell_i \to \ell_j \gamma) = \frac{48\pi^3 \alpha \eta_i}{G_F^2 m_{\ell_i}^2} (|(c_R)_{ji}|^2 + |(c_L)_{ji}|^2), \quad (\eta_\mu = 1, \eta_\tau \approx 1/5)$$

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