Seminar@ KIAS

TeV-scale vector leptoquark from Pati-Salam unification with vectorlike families

Junichiro Kawamura

Institute for Basic Science, CTPU

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in collaboration with

S.Iguro [IPMU], Y.Omura [Kindai U.] and S.Okawa [Victoria U.]

Outline

1. Introduction
2. mass splitting and suppression of $K_L \to \mu e$
3. phenomenology
4. Summary

Leptoquark [LQ]

- carries both baryon and lepton numbers
- scalar S or vector V_μ

$$y\, S\, \overline{Q}\, P_{L,R}\, \ell \quad \text{or} \quad g\, V_\mu\, \overline{Q}\, \gamma^\mu P_{L,R}\, \ell$$

➢ Possible origins

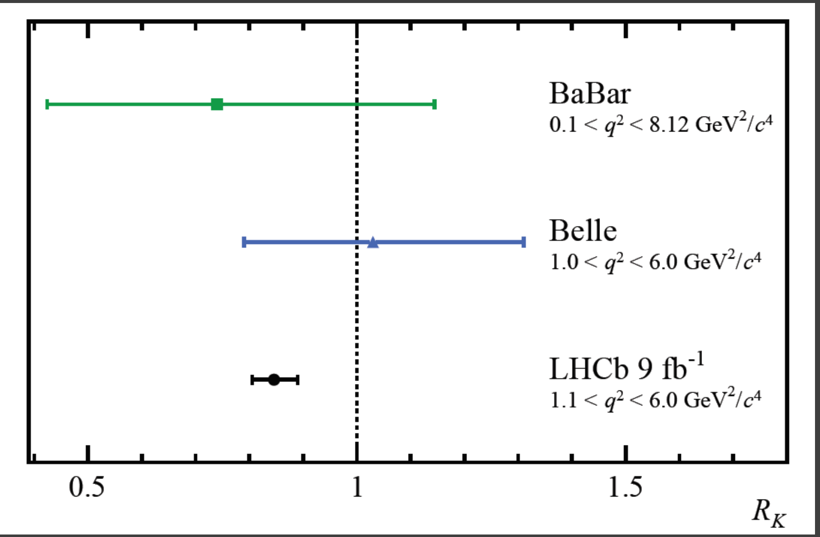
- scalar LQ from R-parity violating supersymmetry
- composite state in technicolor models
- extended gauge/Higgs sector

$b \to s\mu\mu$ anomaly

$$R_K = \frac{\mathrm{Br}(B \to K\mu^+\mu^-)}{\mathrm{Br}(B \to Ke^+e^-)}$$

- SM predicts 1.00 ± 0.01, universal
- $R_K^{1.1<q^2<6.0\ \mathrm{GeV}} = 0.846^{+0.044}_{-0.041}$

→ 3.1σ discrepancy



LHCb, 2103.11769

- Other observables
  - similar results for R_{K^*}
  - discrepancies are also found in angular observables, branching ratio

$b \to s\mu\mu$ anomaly

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\alpha}{4\pi} \sum_{j=9,10} \left(C_j\, \mathcal{O}_j + C_j' \mathcal{O}_j'\right) + h.c.$$

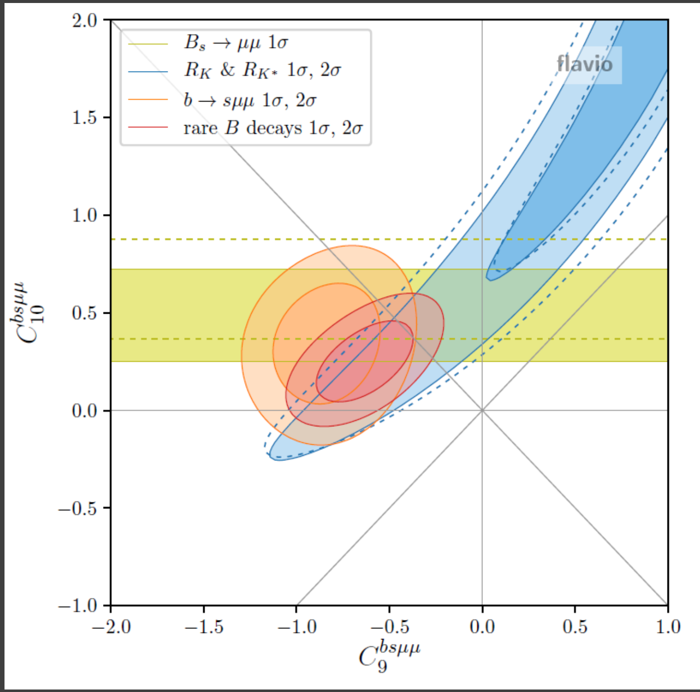
$$\mathcal{O}_9^{(\prime)\mu} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)(\bar{\mu}\gamma^\mu \mu) \qquad \mathcal{O}_{10}^{(\prime)\mu} = \left(\bar{s}\gamma_\mu P_{L(R)} b\right)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

- global fit of (C_9^{NP}, C_{10}^{NP})

fit the Wilson coefficients to all observable related to $b \to s\mu\mu$

→ $C_9^{NP} = -C_{10}^{NP} = -0.41 \pm 0.07$

→ 5.9σ improved from SM



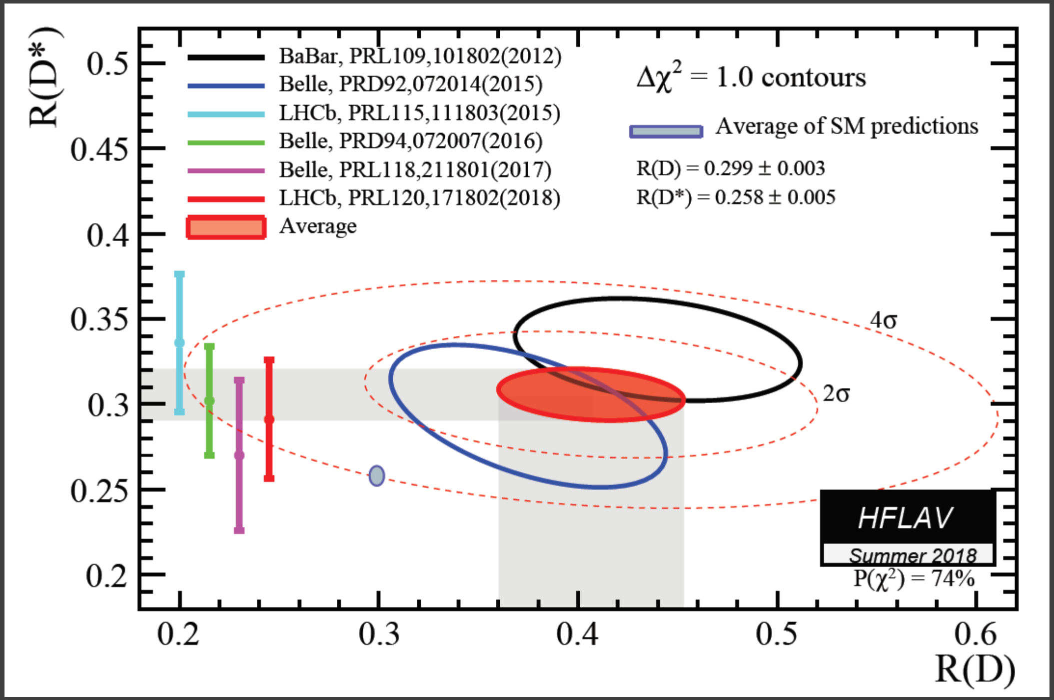
W.Altmannshofer, P.Stangl, 2103.13370

$b \to c\tau\nu$ anomaly

$$R_{D^{(*)}} = \frac{\mathrm{Br}(\bar{B} \to D^{(*)}\tau\nu)}{\mathrm{Br}(\bar{B} \to D^{(*)}\ell\nu)}$$

$$\ell = e, \mu$$

$\sim 3.8\sigma$ discrepancy from SM



HFLAV2018

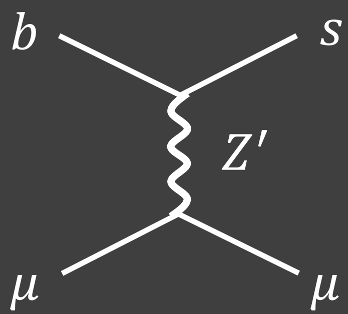
$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + C_{V_1}) O_{V_1} + \cdots \right] \qquad O_{V_1} = (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu)$$

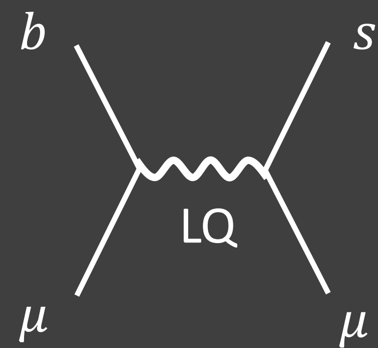
$\rightarrow$ $C_{V_1} \in [0.052, 0.124]$ at 2σ

S.Iguro, M.Takeuchi, R.Watanabe
2011.02486

Explanations for anomalies

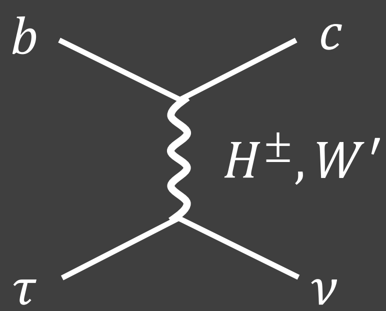
- $b \to s\mu\mu$

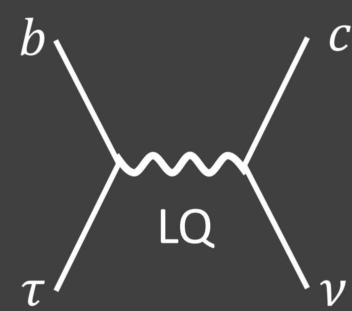




- Z', LQ are possible
- LQ can be scalar/vector

- $b \to c\tau\nu$





- $H^{\pm}, W'$, LQ are possible
- LQ can be scalar/vector

→ LQ can, in principle, explain both anomalies

Pati-Salam [PS] unification

What is an origin of LQ ?

- PS unification: $G_{\mathrm{SM}} \subset G_{\mathrm{PS}} = SU(4)_C \times SU(2)_L \times SU(2)_R$

  - no Abelian gauge symmetry

    → charge quantization: $Q_e + Q_p = 0$

  - no coupling with di-quark couplings unlike $SU(5)$

    → proton is stable, breaking scale can be low

  - quark and lepton are unified $L = \begin{pmatrix} \ell \\ q \end{pmatrix}$ $R = \begin{pmatrix} e & \nu \\ d & u \end{pmatrix}$

    → Yukawa couplings are unified

Pati-Salam [PS] unification

- LQ in PS unification

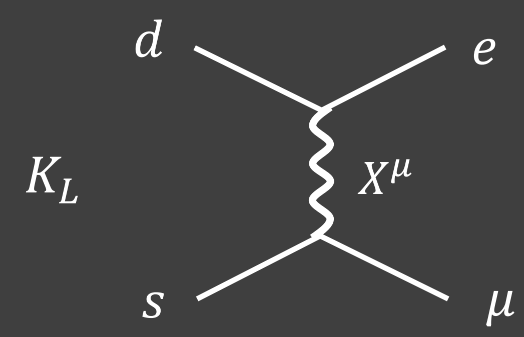
vector LQ arises a gauge boson of $SU(4)_C/SU(3)_C \times U(1)_{B-L}$

$$V^{\mu}_{SU(4)} = \begin{pmatrix} Z^{\mu}_{\mathrm{B}-L} & X^{\mu\dagger} \\ X^{\mu} & G^{\mu} \end{pmatrix}$$

G^{μ}: gluon, Z^{μ}_{B-L}: B-L boson

X^{μ} is vector LQ : $(3,1)_{2/3}$

- Constraints on LQ mass



$$\mathrm{Br}(K_L \to \mu e) \sim \frac{\tau_{K_L}}{1024\pi} \frac{m_K^5 f_K^2}{m_{\mathrm{LQ}}^4 m_s^2}$$

$$\sim 1.4 \times 10^{-11} \times \left(\frac{g_4}{1.0}\right)^4 \left(\frac{1\mathrm{PeV}}{m_{\mathrm{LQ}}}\right)^4 < 4.7 \times 10^{-12} \rightarrow m_{\mathrm{LQ}} > \mathrm{PeV}$$

BNL 1998

too heavy…

Yukawa unification

quark and lepton are unified: $L = \begin{pmatrix} \ell \\ q \end{pmatrix}$ $R = \begin{pmatrix} e & \nu \\ d & u \end{pmatrix}$

→ Yukawa unification

$$\mathcal{L}_{\rm yuk} = -y\, L \Phi R$$

Higgs bi-doublet
$\Phi = \begin{pmatrix} H_u & H_d \end{pmatrix}$

- Sources for Fermion mass splitting

1. renormalization group effects

→ ✓ need large scale separation, typically $\Lambda_{\rm BC} \sim 10^{16}$GeV

2. higher dimensional operators

→ ✓ negligible if cut-off scale is GUT/Planck scale

3. adding matter fields

Goals of this work

build a (minimal) model with TeV-scale LQ from PS

- problems to be solved
  - lepton/quark mass and mixing at tree-level, wo/ RG, higher-dim.
  - suppress $\mathrm{BR}(K_L \to \mu e)$ even with TeV-scale PS breaking
- phenomenology
  - whether the anomalies can be explained or not ?
  - flavor violations induced by LQ
  - flavor violation induced by extra Higgs bosons

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Model with vector-like [VL] fermions

fields	spin	$SU(4)_C$	$SU(2)_L$	$SU(2)_R$
L	1/2	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$
R	1/2	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$
F_L	1/2	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$
F_R	1/2	$\mathbf{4}$	$\mathbf{2}$	$\mathbf{1}$
f_L	1/2	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$
f_R	1/2	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$
Δ	0	$\mathbf{15}$	$\mathbf{1}$	$\mathbf{1}$
Σ	0	$\overline{\mathbf{10}}$	$\mathbf{1}$	$\mathbf{3}$
Φ	0	$\mathbf{1}$	$\mathbf{2}$	$\overline{\mathbf{2}}$

chiral fermions
3 gens.

VL fermions

3 gens. each

Scalars

$$SU(4)_C \times SU(2)_L \times SU(2)_R \xrightarrow{\langle\Delta\rangle} SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\downarrow \langle\Sigma\rangle$$

$$SU(3)_C \times U(1)_{EM} \xleftarrow{\langle\Phi\rangle} SU(3)_C \times SU(2)_L \times U(1)_Y$$

Mass splitting by Higgs bi-doublet

- $SU(2)_L \times SU(2)_R$ bi-doublet Φ

$$\langle\Phi\rangle = (\langle H_u\rangle \quad \langle H_d\rangle) = \begin{pmatrix} v_u & 0 \\ 0 & v_d \end{pmatrix} \qquad SU(2)_L \times U(1)_Y \to U(1)_{EM}$$

- Yukawa couplings $L = \begin{pmatrix} \ell \\ q \end{pmatrix} \qquad R = \begin{pmatrix} e & \nu \\ d & u \end{pmatrix}$

$$-\mathcal{L}_\Phi \supset y_1 \overline{L}\Phi R + y_2\, \overline{L}\epsilon^T \Phi^* \epsilon\, R \qquad\qquad \epsilon = i\sigma_2$$

$$\rightarrow \qquad m_d = v_d y_1 - v_u y_2 \qquad m_u = -v_u y_1 + v_d y_2$$

mass splitting in up-type and down-type fermions

Mass splitting by $SU(4)_C$ adjoint

L.Calibbi, A.Crivelin, T.Li 1709.00692

- $SU(4)_C$ adjoint Δ

$$\langle\Delta\rangle = \frac{v_\Delta}{2\sqrt{3}}\begin{pmatrix} 3 & 0 \\ 0 & -1_3 \end{pmatrix} \qquad SU(4)_C \to SU(3)_C \times U(1)_{B-L}$$

- VL generations: $F_{L/R} = \begin{pmatrix} L_{L/R} \\ Q_{L/R} \end{pmatrix} \quad f_{L/R} = \begin{pmatrix} E_{L/R} & N_{L/R} \\ D_{L/R} & U_{L/R} \end{pmatrix}$

$$-\mathcal{L}_{VL} \supset \underline{M_F \overline{F}_L\, F_R + \kappa\, \overline{F}_L \Delta\, F_R} + \underline{m_F \overline{F}_L\, R + \epsilon\, \overline{F}_L \Delta\, R}$$

$$m_L = M_F + \frac{\sqrt{3}}{2}\kappa\, v_\Delta$$

$$m_Q = M_F - \frac{1}{2\sqrt{3}}\kappa\, v_\Delta$$

mixing of VL and chiral fermions

→ mass splitting in SM generations

Mass matrices

(L, F_L, F_R): $SU(2)_L$ doublet (R, f_L, f_R): $SU(2)_R$ doublet

$$-\mathcal{L}_{\text{mass}} = \begin{pmatrix} \overline{L} & \overline{F}_L & \overline{f}_L \end{pmatrix} \left(\begin{array}{cc|c} \langle\Phi\rangle & \langle\Phi\rangle & m_F + \langle\Delta\rangle \\ \langle\Phi\rangle & \langle\Phi\rangle & M_F + \langle\Delta\rangle \\ \hline m_f + \langle\Delta\rangle & M_f + \langle\Delta\rangle & \langle\Phi\rangle \end{array}\right) \begin{pmatrix} R \\ f_R \\ F_R \end{pmatrix}$$

$\langle\Phi\rangle$: different in up-type (u, ν) and down-type (d, e) fermions

$\langle\Delta\rangle$: different in quarks (u, d) and leptons (ν, e)

- Parametrization $m_{u/d}, \Delta_{u/d} \sim \mathcal{O}(v_H)$, $\mathcal{M}_{L/R}^{\ell/Q} \sim \mathcal{O}(v_\Delta)$

charged leptons $\mathcal{M}_e = \begin{pmatrix} m_d & \mathcal{M}_L^\ell \\ \mathcal{M}_R^\ell & \Delta_d \end{pmatrix}$

down quarks $\mathcal{M}_d = \begin{pmatrix} m_d & \mathcal{M}_L^Q \\ \mathcal{M}_R^Q & \Delta_d \end{pmatrix}$

neutral leptons $\mathcal{M}_\nu^D = \begin{pmatrix} m_u & \mathcal{M}_L^\ell \\ \mathcal{M}_R^\ell & \Delta_u \end{pmatrix}$

up quarks $\mathcal{M}_u = \begin{pmatrix} m_u & \mathcal{M}_L^Q \\ \mathcal{M}_R^Q & \Delta_u \end{pmatrix}$

LQ coupling

$U_L^{f\dagger}\mathcal{M}_f U_R^f = \mathcal{D}_f$: diagonal $f = u, d, e, \nu$

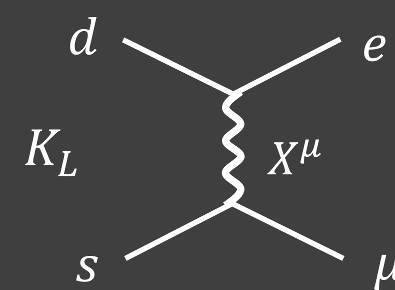
ψ_D: down quarks in mass basis
ψ_E: charged leptons in mass basis

$$\mathcal{L}_{\rm LQ} \supset \frac{g_4}{\sqrt{2}} X^\mu \overline{\psi}_D \gamma_\mu \left(U_L^{d\dagger} U_L^e P_L + U_R^{d\dagger} U_R^e P_R \right) \psi_E$$

→ SM-LQ coupling: $\frac{g_4}{\sqrt{2}} \left[U_{L/R}^{d\dagger} U_{L/R}^e \right]_{ij}$ $i, j = 1,2,3$

→ if SM leptons and quarks are originated from chiral L/R
LQ has $\mathcal{O}(1)$ couplings with $e - d$ and $\mu - s$

→ $m_{\rm LQ} > {\rm PeV}$ for ${\rm Br}(K_L \to e\mu) < 4.7 \times 10^{-12}$



How to suppress ?

Suppression of $K_L \to \mu e$

- Texture for suppressed $K_L \to \mu e$ $\quad (\bar{L} \quad \bar{F}_L \quad \bar{f}_L)\mathcal{M}_f \begin{pmatrix} R \\ f_R \\ F_R \end{pmatrix}$

$$\mathcal{M}_e \sim \begin{pmatrix} 0 & m_e & \mathbf{0} \\ m_d & 0 & M_L^\ell \\ M_R^\ell & \mathbf{0} & 0 \end{pmatrix} \qquad \mathcal{M}_d \sim \begin{pmatrix} 0 & m_e & M_L^Q \\ m_d & 0 & \mathbf{0} \\ \mathbf{0} & M_R^Q & 0 \end{pmatrix}$$

→ SM leptons are from chiral L and vectorlike f_R

SM quarks are from vectorlike F_L and chiral R

→ LQ couplings $g_L^X \sim (g_R^X)^T \sim \frac{g_4}{\sqrt{2}} \begin{pmatrix} \mathbf{0} & 0 & 1_3 \\ 1_3 & 0 & 0 \\ 0 & 1_3 & 0 \end{pmatrix}$

→ No electron-down quark coupling in this limit

Caveat ☠

- Texture for suppressed $K_L \to \mu e$ $\quad (\bar{L} \quad \bar{F}_L \quad \bar{f}_L)\mathcal{M}_f \begin{pmatrix} R \\ f_R \\ F_R \end{pmatrix}$

$$\mathcal{M}_e \sim \begin{pmatrix} 0 & m_e & \mathbf{0} \\ m_d & 0 & M_L^\ell \\ M_R^\ell & \mathbf{0} & 0 \end{pmatrix} \qquad \mathcal{M}_d \sim \begin{pmatrix} 0 & m_e & M_L^Q \\ m_d & 0 & \mathbf{0} \\ \mathbf{0} & M_R^Q & 0 \end{pmatrix}$$

↑

$m_f + \kappa\langle\Delta\rangle \sim 0$ (fine-) tuning to realize the texture

- Explanations for $b \to s\mu\mu, b \to c\tau\nu$ anomalies
  - need couplings with SM fermions
  - violation of the cancellation would be favored

Summary

PS model with VL fermions

$$\mathcal{M}_e \sim \begin{pmatrix} 0 & \boldsymbol{m_e} & \mathbf{0} \\ m_d & 0 & M_L^\ell \\ M_R^\ell & \mathbf{0} & 0 \end{pmatrix} \qquad \mathcal{M}_d \sim \begin{pmatrix} 0 & m_e & M_L^Q \\ \boldsymbol{m_d} & 0 & \mathbf{0} \\ \mathbf{0} & M_R^Q & 0 \end{pmatrix}$$

$$\mathcal{M}_n \sim \begin{pmatrix} 0 & \boldsymbol{m_n} & \mathbf{0} \\ m_u & 0 & M_L^\ell \\ M_R^\ell & \mathbf{0} & 0 \end{pmatrix} \qquad \mathcal{M}_u \sim \begin{pmatrix} 0 & m_n & M_L^Q \\ \boldsymbol{m_u} & 0 & \mathbf{0} \\ \mathbf{0} & M_R^Q & 0 \end{pmatrix}$$

splitting by $\langle\Phi\rangle, \langle\Delta\rangle$. $K_L \to \mu e$ is suppressed by the above texture

- Can the anomalies be explained ?
- how severe tuning of parameters are required ?
- how can the model be tested ?

Outline

1. Introduction
2. mass splitting and suppression of $K_L \to \mu e$
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4. Summary and discussions

LQ coupling with SM fermions

$$\mathcal{M}_e \sim \begin{pmatrix} 0 & m_e & m_R^\ell \\ m_d & 0 & M_L^\ell \\ M_R^\ell & m_R^\ell & \Delta_d \end{pmatrix} \qquad \mathcal{M}_d \sim \begin{pmatrix} 0 & m_e & m_L^Q \\ m_d & 0 & M_L^Q \\ m_R^Q & M_R^Q & \Delta_d \end{pmatrix}$$

with

$$\begin{pmatrix} M_R^\ell & m_R^\ell \end{pmatrix} = \begin{pmatrix} D_{\mathrm{R}}^\ell & 0 \end{pmatrix} V_{\ell_R}^\dagger \qquad \begin{pmatrix} m_R^Q & M_R^Q \end{pmatrix} = \begin{pmatrix} 0 & D_R^Q \end{pmatrix} V_{Q_R}^\dagger$$

$$\begin{pmatrix} m_R^\ell \\ M_L^\ell \end{pmatrix} = V_{\ell_L} \begin{pmatrix} 0 \\ D_L^\ell \end{pmatrix} \qquad \begin{pmatrix} m_R^\ell \\ M_L^\ell \end{pmatrix} = V_{\ell_L} \begin{pmatrix} 0 \\ D_L^\ell \end{pmatrix}$$

$V_{\ell_L}, V_{\ell_R}, V_{Q_L}, V_{Q_R}$: 6 × 6 unitary matrices $\qquad$ $D_R^\ell, D_L^\ell, D_R^Q, D_L^Q$: 3 × 3 diagonal matrices

→ LQ couplings to SM families: $i, j = 1,2,3$

$$\left[g_{d_L}^X\right]_{ij} \sim \frac{g_4}{\sqrt{2}} \left[V_{Q_L}^\dagger V_{\ell_L}\right]_{3+i,j} \qquad \left[g_{d_R}^X\right]_{ij} \sim \frac{g_4}{\sqrt{2}} \left[V_{Q_R}^\dagger V_{\ell_R}\right]_{i,j+3}$$

Parametrization of unitary matrices

V_{F_X} $(F = \ell, Q, X = L, R)$ directly determine LQ couplings

$$V_{F_X} = R_{F_X}^{11} R_{F_X}^{12} R_{F_X}^{13} R_{F_X}^{21} R_{F_X}^{22} R_{F_X}^{23} R_{F_X}^{31} R_{F_X}^{32} R_{F_X}^{33}$$

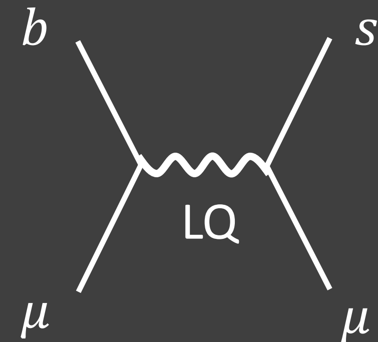
$$\text{ex. } R_{F_X}^{23} = \left(\begin{array}{ccc|ccc} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & c_{F_X}^{23} & 0 & 0 & 0 & s_{F_X}^{23} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -s_{F_X}^{23} & 0 & 0 & 0 & c_{F_X}^{23} \end{array}\right)$$

$$\left(c_{F_X}^{23}\right)^2 + \left(s_{F_X}^{23}\right)^2 = 1$$

*assumed to be real,

We shall assume $s_{F_X}^{ij}$ are universal for i, j, except $s_{F_L}^{23}, s_{F_L}^{22}$
(and small)

$b \to s\mu\mu$ anomaly



LQ couplings to SM families: $\left[g^X_{d_L}\right]_{ij} \sim \frac{g_4}{\sqrt{2}}\left[V^\dagger_{Q_L} V_{\ell_L}\right]_{3+i,j}$

→ $$C_9^{NP} = -C_{10}^{NP} = -\frac{\sqrt{2}\,4\pi}{4G_F\alpha}\frac{1}{V^*_{tb}V_{ts}} \times \frac{1}{2m^2_{\rm LQ}}\left[g^X_{d_L}\right]^*_{b\mu}\left[g^X_{d_L}\right]_{s\mu}$$

$$\sim -0.51 \times \left(\frac{5\ \mathrm{TeV}}{m_{\rm LQ}}\right)^2\left(\frac{\left[g^X_{d_L}\right]^*_{b\mu}\left[g^X_{d_L}\right]_{s\mu}}{0.02}\right)$$

c.f. 1σ range: $C_9^{NP} \in [-0.59, -0.41]$

- We take $s^{23}_{Q_L} = -s^{23}_{\ell_L} = 1/\sqrt{2}\,, s^{22}_{Q_L} = -s^{22}_{\ell_L} = 0.04 \times 1/\sqrt{2}$

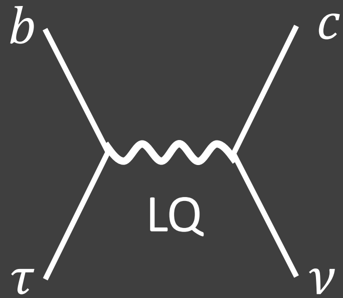
$$\left[g^X_{d_L}\right]_{b\mu} \sim \frac{g_4}{2\sqrt{2}}, \left[g^X_{d_L}\right]_{s\mu} = 0.04 \times \frac{g_4}{2\sqrt{2}}$$

$g_4 \sim g_3(\mathrm{TeV}) \sim 1$

→ $b \to s\mu\mu$ anomaly can be explained for $m_{\rm LQ} \lesssim 5\ \mathrm{TeV}$

$b \to c\tau\nu$ anomaly

LQ couplings to SM families: $[g_{d_L}^X]_{ij} \sim \frac{g_4}{\sqrt{2}} [V_{Q_L}^\dagger V_{\ell_L}]_{3+i,j}$



$$\rightarrow \quad C_{V_1}^{NP} = -\frac{\sqrt{2}}{4G_F} \frac{1}{V_{cb}} \times \frac{1}{m_{\rm LQ}^2} [g_{d_L}^X]_{b\tau}^* [g_{u_L}^X]_{c\nu_\tau}$$

$$\sim 0.092 \times \left(\frac{1.4\ \mathrm{TeV}}{m_{\rm LQ}}\right)^2 \left(\frac{[g_{d_L}^X]_{b\tau}^* [g_{u_L}^X]_{c\nu_\tau}}{0.25}\right)$$

c.f. 2σ range is $C_{V_1}^{NP} \in [0.052, 0.124]$

- maximal size of coupling

$$[g_{d_L}^X]_{b\tau}^* [g_{u_L}^X]_{c\nu_\tau} < \frac{g_4^2}{4} \sim 0.25$$

$$g_4 \sim g_3(\mathrm{TeV}) \sim 1$$

→ $b \to c\tau\nu$ anomaly can be explained if $m_{\rm LQ} \lesssim 1.4$ TeV

Z' boson search

- upper bound on Z' mass

$$Z'\text{boson: } m_{Z'}^2 \sim \frac{4g_4^2 + 2g_R^2}{2} v_\Sigma^2 \qquad \text{LQ : } m_{\text{LQ}}^2 \sim g_4^2 \left(\frac{4}{3} v_\Delta^2 + \frac{1}{2} v_\Sigma^2 \right)$$

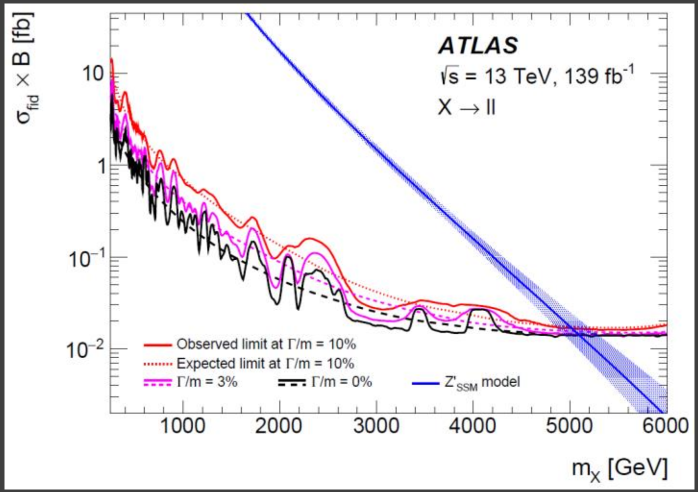
$$\rightarrow \quad m_{Z'} < \sqrt{\frac{2g_R^2 + 3g_4^2}{g_4^2}} m_{\text{LQ}} \sim 3.5\ \text{TeV} \times \left(\frac{m_{\text{LQ}}}{1.8\ \text{TeV}} \right)$$

- dilepton search for Z' boson at LHC

$$m_{Z'} > 5\ \text{TeV if Br}(Z' \to \ell\ell) \sim 0.1$$

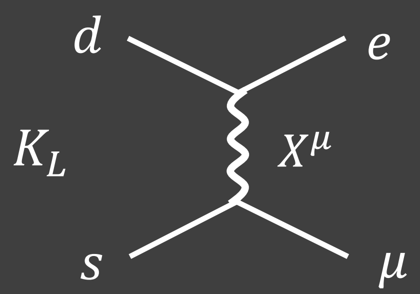
*relaxed to 4.5 TeV if $m_{Z'} > m_{\text{VL}}$

$\rightarrow$ $b \to c\tau\nu$ can not be explained by the LQ X_μ

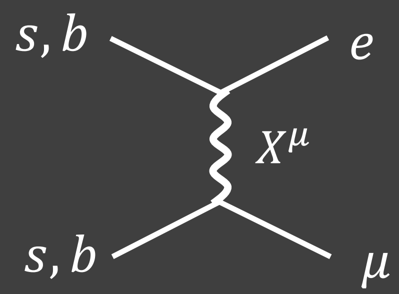


$\mu - e$ flavor violation by LQ

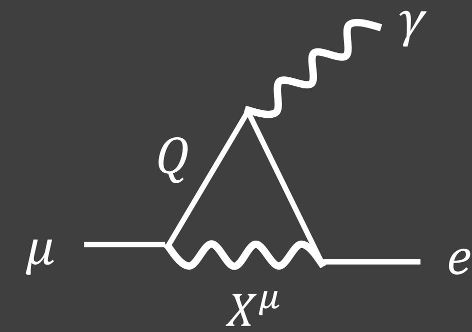
- $K_L \to \mu e$



- $\mu - e$ conversion



- $\mu \to e\gamma$



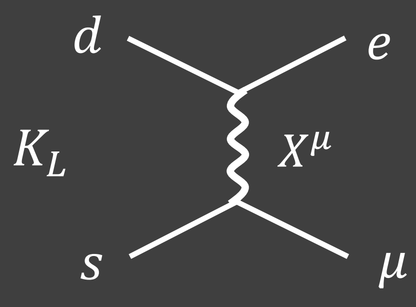
- Assuming $\left[g^X_{d_L}\right]_{s\mu} \gg$ others

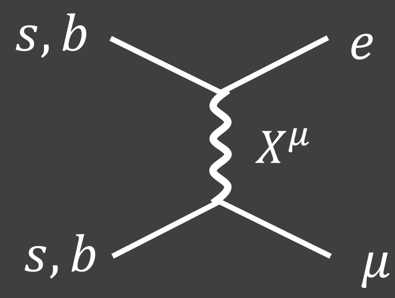
$$\mathrm{BR}(K_L \to \mu e) \sim 2.3 \times 10^{-12} \times \left(\frac{5\ \mathrm{TeV}}{m_{\mathrm{LQ}}}\right)^4 \left(\frac{\left[g^X_{d_L}\right]^*_{s\mu} \left[g^X_{d_R}\right]_{de}}{10^{-5}}\right)$$

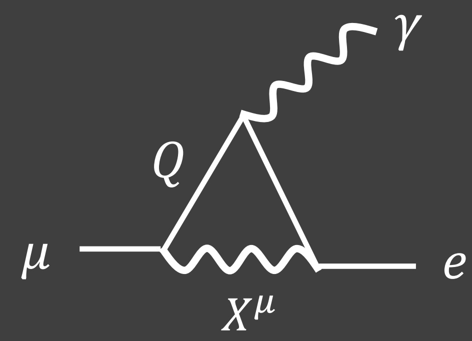
→ $\left[g^X_{d_R}\right]_{de} < \mathcal{O}(10^{-3})$ for $m_{\mathrm{LQ}} \sim 5\ \mathrm{TeV}$ and $\left[g^X_{d_L}\right]_{s\mu} \sim 0.01$

$\mu - e$ flavor violation by LQ

- $K_L \to \mu e$
- $\mu - e$ conversion
- $\mu \to e\gamma$







- Assuming $[g_{d_L}^X]_{s\mu}, [g_{d_L}^X]_{b\mu} \gg$ others

$$\mathrm{BR}(\mu \to e)^{\mathrm{Al}}$$

$$\sim 1.5 \times 10^{-14} \times \left(\frac{5\ \mathrm{TeV}}{m_{\mathrm{LQ}}}\right)^2 \left| 0.45 \left(\frac{[g_{d_L}^X]_{s\mu}^* [g_{d_R}^X]_{se}}{10^{-5}}\right) + 0.016 \left(\frac{[g_{d_L}^X]_{b\mu}^* [g_{d_R}^X]_{be}}{10^{-5}}\right)\right|^2$$

→ Well above the future sensitivity $\sim 10^{-17}$ at DeeMe/COMET/Mu2e

$\mu \to e\gamma$ and $(g-2)_\mu$

- $\Delta_d < \mathcal{O}(v_d)$

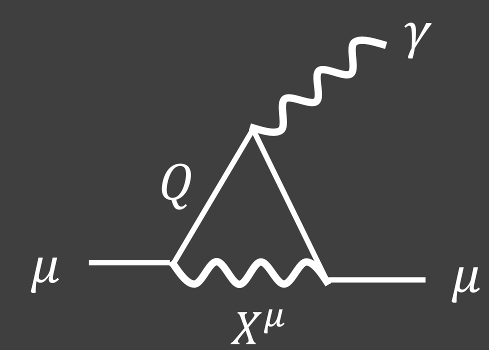
$$\mathcal{M}_d \sim \begin{pmatrix} 0 & m_e & m_L^Q \\ m_d & 0 & M_L^Q \\ m_R^Q & M_R^Q & \Delta_d \end{pmatrix}$$

$$\mathrm{BR}(\mu \to e\gamma) \sim 1.2 \times 10^{-13} \times \left(\frac{5\ \mathrm{TeV}}{m_{\mathrm{LQ}}}\right)^4 \left(\frac{g_L^X g_R^X}{0.005}\right)^2 \left(\frac{\Delta_d}{100\ \mathrm{MeV}}\right)^2 < 4.2 \times 10^{-13} \quad \text{MEG}$$

$g_{L/R}^X$: LQ coupling of SM lepton and VL quarks in L/R current

- muon g-2

$$\Delta a_\mu < 5 \times 10^{-11} \times \left(\frac{5\ \mathrm{TeV}}{m_{\mathrm{LQ}}}\right)^2 \left(\frac{\Delta_d}{100\ \mathrm{MeV}}\right)$$

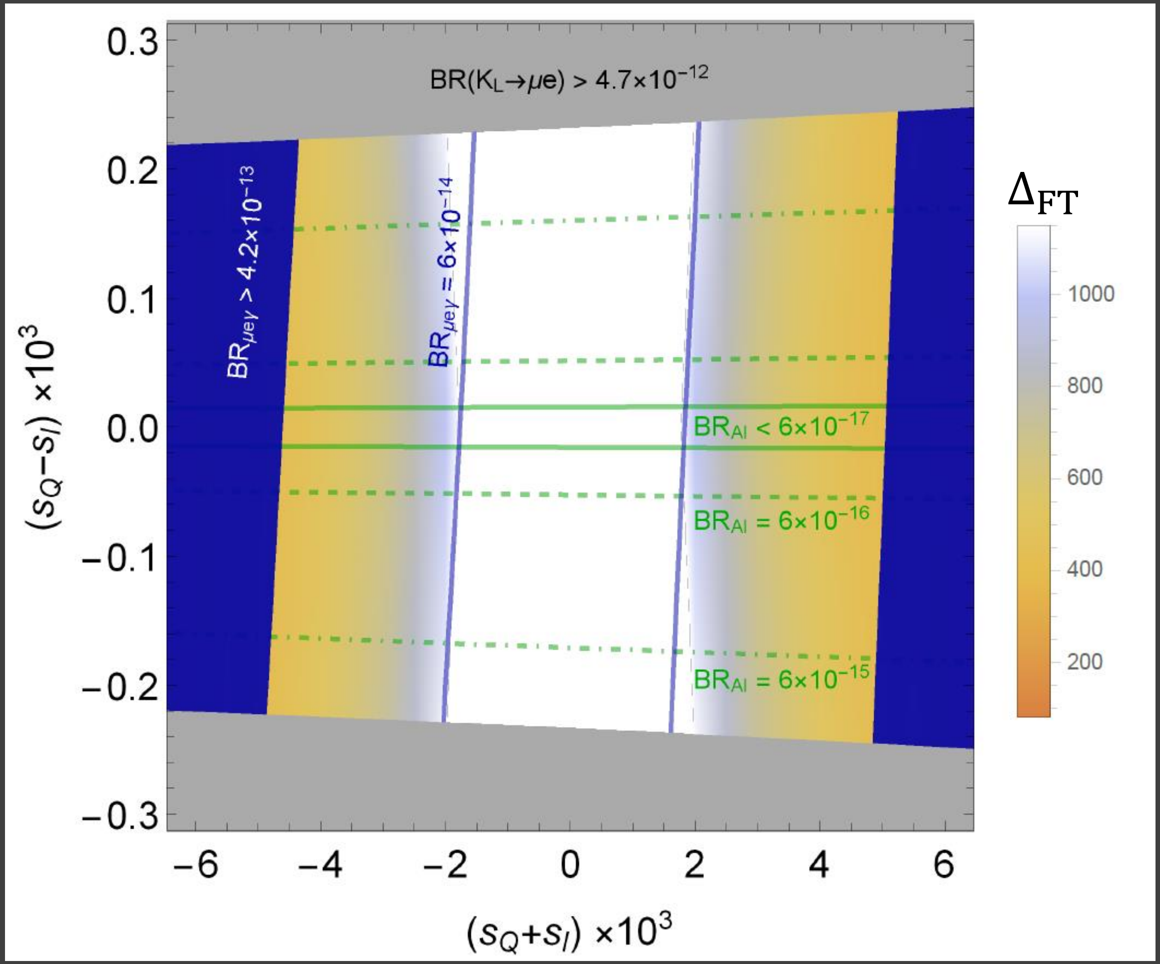


→ $\Delta a_\mu \sim 10^{-9}$ is explained if $\Delta_d > 10$ GeV for μ is allowed

$\mu - e$ flavor violation by LQ

turning on mixing angles of other flavors universally with $b \to s\mu\mu$ explained

$$s_Q = s_{Q\,L,R}^{\;ij}, \quad s_\ell = s_{\ell\,L,R}^{\;ij} \qquad (i,j) \neq (2,2), (2,3) \text{ for } L$$



$$\mathcal{M}_d \sim \begin{pmatrix} 0 & m_e & m_L^Q \\ m_d & 0 & M_L^Q \\ m_R^Q & M_R^Q & \Delta_d \end{pmatrix}$$

$$\Delta_{\mathrm{FT}} = \frac{\max(m_{L,R}^{\ell,Q}, M_{L,R}^{\ell,Q})}{\min(m_{L,R}^{\ell,Q}, M_{L,R}^{\ell,Q})}$$

$\Delta_{\mathrm{FT}} > 500 \leftrightarrow 0.2\,\%$ tuning

Flavor violation by Higgs boson

- $SU(2)_L \times SU(2)_R$ bi-doublet $\Phi = (H_u \quad H_d)$

$$-\mathcal{L}_\Phi \supset y_1 \overline{L} \Phi R + y_2 \overline{L} \epsilon^T \Phi^* \epsilon R \qquad \epsilon = i\sigma_2$$

→ up-down mass splitting

$$m_d = v_d y_1 - v_u y_2$$

$$m_u = -v_u y_1 + v_d y_2$$

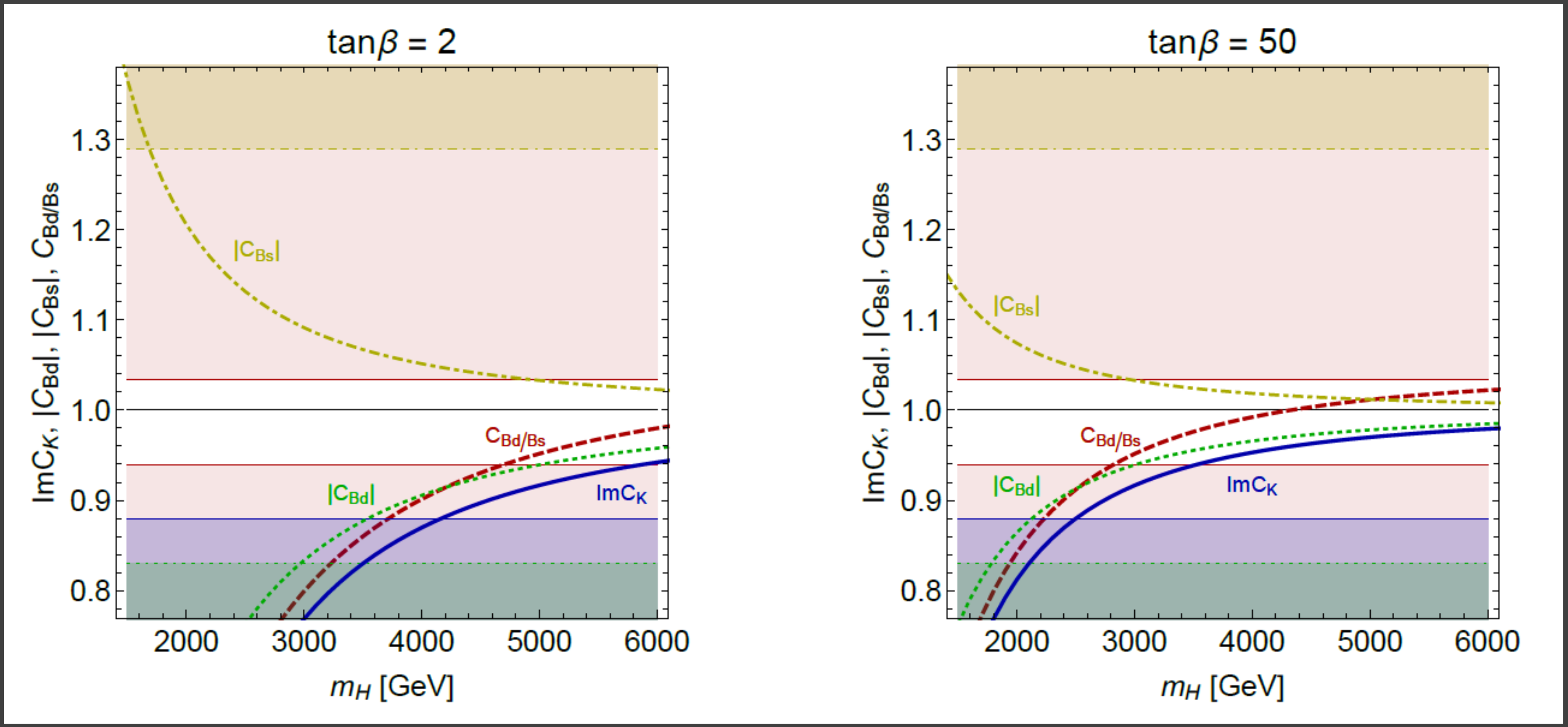
- Flavor violating Yukawa couplings

$$Y_d^H \sim \frac{1}{\sqrt{2} v_H} V_{\rm CKM}^\dagger \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} \sim \frac{1}{\sqrt{2}} \begin{pmatrix} 10^{-4} & 0.0006 & 0.007 \\ 10^{-6} & 0.003 & 0.03 \\ 10^{-8} & 10^{-4} & 0.78 \end{pmatrix}$$

→ flavor violation by extra Higgs bosons

Flavor violation by Higgs boson

Constraints from neutral meson mixing $C_M = \frac{\langle M|H_{\Delta F=2}|\overline{M}\rangle}{\langle M|H^{\rm SM}_{\Delta F=2}|\overline{M}\rangle}$ $M = K, B_d, B_s$



- ratio $C_{B_d/B_s} = \left(\frac{\Delta M_s}{\Delta M_d}\right)_{\rm SM} \left|\frac{\langle B_d|H_{\Delta F=2}|\overline{B}_d\rangle}{\langle B_s|H_{\Delta F=2}|\overline{B}_s\rangle}\right|$ gives strongest bound

L.D.Luzio, M.Kirk, A.Lenz, T.Rauh, 1909.11087

- $m_H > 4.8\ \ (2.8)$ TeV for $\tan\beta = \langle v_u\rangle/\langle v_d\rangle = 2\ \ (50)$

Discussion

- TeV-scale vector LQ from PS model with VL families
  - lepton/quark mass and mixing at tree-level via $\langle\Delta\rangle, \langle\Phi\rangle$
  - $\mathrm{BR}(K_L \to \mu e)$ is suppressed by assuming the cancellation of $\mathcal{O}(0.2\%)$

- phenomenology
  - $b \to s\mu\mu$ is explained, while $b \to c\tau\nu$ is not by Z' search
  - $\mu -$ e conversion is promising to test the model
  - Higgs flavor violation is also predicted for mass splitting
  - More detailed analysis with loop corrections are in progress

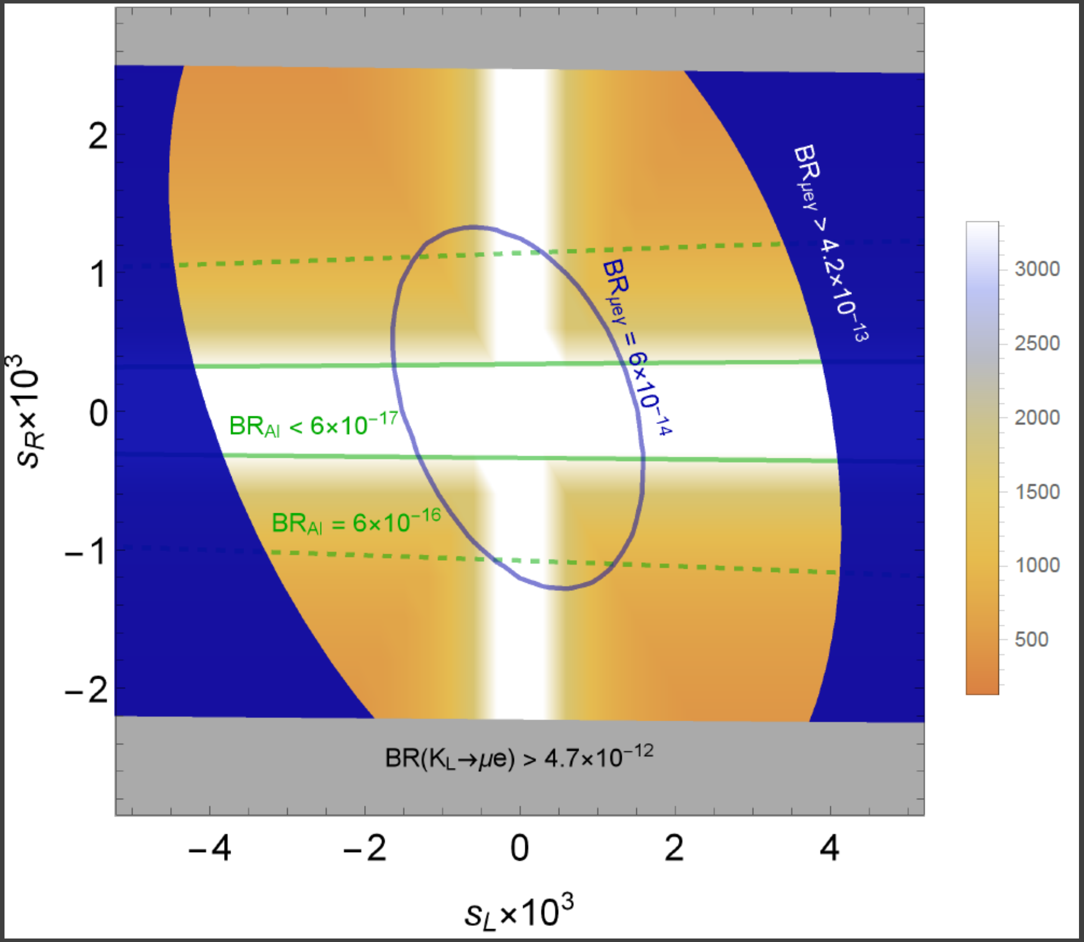
Thank you !

Backup

$\mu - e$ flavor violation via LQ

turning on mixing angles with other flavors universally with $b \to s\mu\mu$ explained

$$s_{L/R} = s^{ij}_{Q_{L/R}} = -s^{ij}_{\ell_{L/R}}/1.1 \qquad (i,j) \neq (2,2),(2,3) \text{ for } L$$



$$\mathcal{M}_d \sim \begin{pmatrix} 0 & m_e & m_L^Q \\ m_d & 0 & M_L^Q \\ m_R^Q & M_R^Q & \Delta_d \end{pmatrix}$$

$$\Delta_{FT} = \frac{\max(m^{\ell,Q}_{L,R}, M^{\ell,Q}_{L,R})}{\min(m^{\ell,Q}_{L,R}, M^{\ell,Q}_{L,R})}$$

$\Delta_{FT} > 500 \leftrightarrow$ 0.2 % tuning

Neutrino

- Majorana mass

$$-\mathcal{L}_{\text{Maj}} = \frac{h}{2}\overline{f}^c_R \epsilon^T \Sigma\, f_R \qquad \Sigma = \tau^{k_R}\Sigma^{k_R}_{\alpha\beta} : \left(\overline{10}, 1,3\right)$$

$k_R = 1,2,3 : SU(2)_R$

$\alpha, \beta = 1,2,3,4 : SU(4)_C$

$\big\downarrow \ \langle \Sigma^+_{11} \rangle = v_\Sigma / \sqrt{2}$

$$-\mathcal{L}_{\text{Maj}} = \frac{h}{2}\frac{v_\Sigma}{\sqrt{2}}\overline{\mathcal{N}}^c_R \epsilon^T\, \mathcal{N}_R$$

- Mass matrix

$\downarrow$ see-saw

$$\mathcal{M}_N = \begin{pmatrix} 0 & \mathcal{M}_D \\ \mathcal{M}_D^T & \mathcal{M}_M \end{pmatrix}$$

$$\mathcal{M}_D \sim \begin{pmatrix} 0 & \boldsymbol{m_n} & 0 \\ m_u & 0 & M_{\ell_L} \\ M_{\ell_R} & 0 & 0 \end{pmatrix}$$

$$\mathcal{M}_M \sim \frac{v_\Sigma}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & h & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

CKM and PMNS matrices

- Masses for up sector in “canonical” case

$$\mathcal{M}_u \sim \begin{pmatrix} 0 & \boldsymbol{m_n} & M_{Q_L} \\ m_u & 0 & 0 \\ 0 & M_{Q_R} & 0 \end{pmatrix} \qquad \mathcal{M}_n \sim \begin{pmatrix} 0 & \boldsymbol{m_n} & 0 \\ m_u & 0 & M_{\ell_L} \\ M_{\ell_R} & 0 & 0 \end{pmatrix}$$

$m_n = U_{\text{PMNS}}\, d_n \quad m_u = V_{\text{CKM}}^{\dagger} d_u \quad d_n, d_u$: diagonal

- W-boson couplings of quarks at benchmark

$$\begin{pmatrix}
0.9745 & 0.2245 & 0.0036 \cdot e^{-1.20i} & 0.0000 & 0.0000 \cdot e^{-0.49i} & 0.0000 \cdot e^{-0.30i} & 0.0000 \cdot e^{-0.43i} & 0.0000 \cdot e^{2.80i} & 0.0000 \cdot e^{-3.10i} \\
0.2244 \cdot e^{-3.10i} & 0.9736 & 0.0421 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \cdot e^{-3.10i} & 0.0000 \cdot e^{-3.10i} \\
0.0090 \cdot e^{-0.38i} & 0.0413 \cdot e^{-3.10i} & 0.9991 & 0.0000 \cdot e^{0.02i} & 0.0000 \cdot e^{3.10i} & 0.0007 \cdot e^{-3.10i} & 0.0000 \cdot e^{-3.10i} & 0.0002 \cdot e^{-3.10i} & -0.0000 \\
0.0000 \cdot e^{-0.42i} & 0.0000 \cdot e^{-3.10i} & 0.0000 & 0.0000 \cdot e^{1.50i} & 0.9991 & 0.0007 \cdot e^{-3.10i} & 0.0298 \cdot e^{-3.10i} & 0.0002 \cdot e^{-3.10i} & 0.0000 \cdot e^{1.40i} \\
0.0000 \cdot e^{-2.80i} & 0.0000 \cdot e^{0.73i} & 0.0000 \cdot e^{-2.40i} & 0.7621 \cdot e^{0.72i} & 0.0000 \cdot e^{3.00i} & 0.0000 & 0.0000 \cdot e^{-0.33i} & 0.0000 \cdot e^{-2.30i} & 0.6468 \cdot e^{0.72i} \\
0.0000 \cdot e^{-0.22i} & 0.0000 \cdot e^{-3.10i} & 0.0000 & 0.0002 \cdot e^{-0.03i} & 0.0290 & 0.0025 & 0.0009 \cdot e^{-3.10i} & 0.0005 & 0.0002 \cdot e^{-0.03i} \\
0.0000 \cdot e^{-0.41i} & 0.0000 \cdot e^{-3.10i} & 0.0000 \cdot e^{-0.01i} & 0.0000 \cdot e^{1.00i} & 0.0002 \cdot e^{-3.10i} & 0.0029 & 0.0000 & 0.0006 & 0.0000 \cdot e^{1.00i} \\
0.0000 \cdot e^{-1.30i} & 0.0000 \cdot e^{2.10i} & 0.0000 \cdot e^{-1.00i} & 0.0227 \cdot e^{-1.00i} & 0.0001 \cdot e^{-3.10i} & 0.0028 \cdot e^{-1.00i} & 0.0000 \cdot e^{-0.73i} & 0.0005 \cdot e^{-1.00i} & 0.0193 \cdot e^{-1.00i} \\
0.0000 \cdot e^{-0.36i} & 0.0000 \cdot e^{-3.10i} & 0.0007 \cdot e^{0.03i} & 0.0001 \cdot e^{-3.10i} & 0.0008 \cdot e^{0.01i} & 0.9819 \cdot e^{0.03i} & 0.0034 \cdot e^{0.03i} & 0.1894 \cdot e^{0.03i} & 0.0000 \cdot e^{-0.26i}
\end{pmatrix}$$

PMNS matrix is also explained

Parametrization

$$\mathcal{M}_d = \begin{pmatrix} \widetilde{D}_d & V_{Q_L}\widetilde{D}_{Q_L}W^\dagger_{Q_R} \\ W_{Q_L}\widetilde{D}_{Q_R}V^\dagger_{Q_R} & \Delta_d \end{pmatrix}, \quad \mathcal{M}_e = \begin{pmatrix} \widetilde{D}_d & V_{\ell_L}\widetilde{D}_{\ell_L}W^\dagger_{\ell_R} \\ W_{\ell_L}\widetilde{D}_{\ell_R}V^\dagger_{\ell_R} & \Delta_d \end{pmatrix},$$

$$\mathcal{M}_u = \begin{pmatrix} v_{u_L}\widetilde{D}_u v^\dagger_{u_R} & V_{Q_L}\widetilde{D}_{Q_L}W^\dagger_{Q_R} \\ W_{Q_L}\widetilde{D}_{Q_R}V^\dagger_{Q_R} & w_{u_L}\Delta_u w^\dagger_{u_R} \end{pmatrix}, \quad \mathcal{M}_n = \begin{pmatrix} v_{u_L}\widetilde{D}_u v^\dagger_{u_R} & V_{\ell_L}\widetilde{D}_{\ell_L}W^\dagger_{\ell_R} \\ W_{\ell_L}\widetilde{D}_{\ell_R}V^\dagger_{\ell_R} & w_{u_L}\Delta_u w^\dagger_{u_R} \end{pmatrix},$$

where

$$\widetilde{D}_d = \begin{pmatrix} 0_3 & D_e \\ D_d & 0_3 \end{pmatrix}, \quad \widetilde{D}_u = \begin{pmatrix} 0_3 & D_n \\ D_u & 0_3 \end{pmatrix},$$

and

$$\widetilde{D}_{Q_R} = \begin{pmatrix} 0_3 & D_{Q_R} \end{pmatrix}, \quad \widetilde{D}_{Q_L} = \begin{pmatrix} D_{Q_L} \\ 0_3 \end{pmatrix}, \quad \widetilde{D}_{\ell_R} = \begin{pmatrix} D_{\ell_R} & 0_3 \end{pmatrix}, \quad \widetilde{D}_{\ell_L} = \begin{pmatrix} 0_3 \\ D_{\ell_L} \end{pmatrix}.$$

$V_{F_{L/R}}, v_{F_{L/R}}$: 6×6 unitary $W_{F_{L/R}}, w_{F_{L/R}}$: 3×3 unitary $D_{e,n,u,d}, D_{F_{L/R}}, \Delta_{u,d}$: 3×3 diagonal

$W_{F_{L/R}}, w_{F_{L/R}}$ are taken to be identity, $D_{F_{L/R}}, \Delta_{u,d}$ are proportional to identity

$V_{F_{L/R}}, v_{F_{L/R}}, D_{e,n,u,d}$ are fitted to explain SM fermion masses and mixing

Coupling of Adjoint Δ

$$\Delta = \frac{1}{2\sqrt{3}}\left(v_\Delta + \frac{h_\Delta}{\sqrt{2}}\right)\begin{pmatrix} 3 & 0 \\ 0 & -1_3 \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & \Delta_8 \end{pmatrix}$$

- Yukawa couplings to Δ in mass basis

$$Y^e_\Delta \sim \begin{pmatrix} \mathbf{0} & 0 & \Lambda_{L_1} \\ \Lambda_{R_1} & \Lambda_{R_2} & 0 \\ 0 & 0 & \Lambda_{L_2} \end{pmatrix} + \mathcal{O}(\frac{v_H}{v_\Delta})$$

$$(\Lambda_{R_1} \quad \Lambda_{R_2}) = \widetilde{D}_{\ell_R} - W^\dagger_{\ell_L} W_{Q_L}\, \widetilde{D}_{Q_R} V^\dagger_{Q_R} V_{\ell_R} \qquad \begin{pmatrix} \Lambda_{L_1} \\ \Lambda_{L_2} \end{pmatrix} = \widetilde{D}_{\ell_L} - V^\dagger_{\ell_L} V_{Q_L}\, \widetilde{D}_{Q_L} W^\dagger_{Q_R} W_{\ell_R}$$

No Δ couplings to SM fermions at leading order

Coupling of Σ and $n-\overline{n}$ oscillation

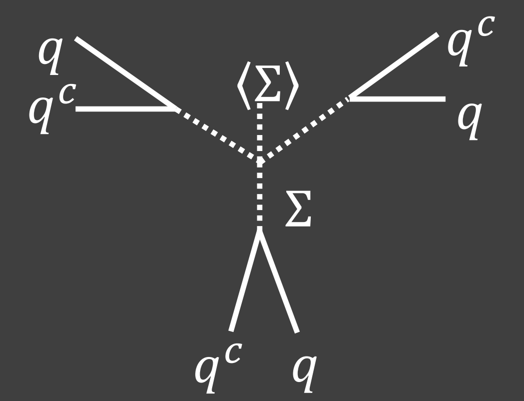
- Discrete Z_3 symmetry after PS breaking

R.N.Mohapatra, R.E. Marshak, PRL44(1980)1316-1319

$$\Sigma_{ab} \to e^{-2i\pi/3}\Sigma_{ab}, \qquad \Sigma_{a1} \to e^{-i\pi/3}\Sigma_{a1}, \qquad \Sigma_{11} \to \Sigma_{11},$$
$$\mathbf{u}_{L,R} \to e^{i\pi/3}\mathbf{u}_{L,R}, \qquad \mathbf{d}_{L,R} \to e^{i\pi/3}\mathbf{d}_{L,R},$$

proton decay is forbidden, but $n-\overline{n}$ oscillation is not

$$\tau_{n-\overline{n}} \sim \frac{m_\Sigma^6}{\lambda_\Sigma v_\Sigma h_Q^3}\frac{1}{\Lambda_{\rm QCD}^6}$$
$$\sim 1.2\times 10^{14}\,\sec \times \left(\frac{m_\Sigma}{10\,\rm TeV}\right)^6 \left(\frac{10\,\rm TeV}{v_\Sigma}\right) \left(\frac{180\,\rm MeV}{\Lambda_{\rm QCD}}\right)^6 \left(\frac{0.005}{s_Q}\right)^6 \left(\frac{1.0}{h}\right)^3 \left(\frac{0.1}{\lambda_\Sigma}\right)$$



much below experimental bound $< \mathcal{O}(10^8\ \mathrm{sec})$

Super-Kamiokande