Footprints of LQs: from B to K rare decays

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Outline

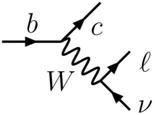
1. Introduction
2. $s \to d\nu\bar{\nu}$ transitions
3. Pheno of two LQ models
4. Results for $K \to \pi\nu\bar{\nu}$

Outline

B-physics anomalies

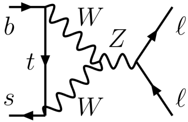
SM $\sim$ respects LFU (Lepton Flavor Universality) $\Rightarrow$ $R_X^{q^2_{\ell\ell} \gg m^2_\ell} \simeq 1$

[talks by (exp) Lucio Martinez, Franco Lima, Urquijo, Patel; (theo) Matias, Neshatpour, Valli, Hurth]



Charged Currents

$R_{D^{(*)}} = \frac{\mathcal{B}(B^0 \to D^{(*)-} \tau^+ \nu)}{\mathcal{B}(B^0 \to D^{(*)-} (e^+, \mu^+) \nu)}$	$R_{J/\psi} = \frac{\mathcal{B}(B_c^+ \to (J/\psi) \tau^+ \nu)}{\mathcal{B}(B_c^+ \to (J/\psi) \mu^+ \nu)}$
[BaBar, Belle; BaBar, Belle, LHCb]	[LHCb'17]
$\sim 2 - 3.4\sigma$ (w/ SM)	$\sim 2\sigma$ (w/ SM)



$+ \ldots$

Neutral Currents

$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)} e^+ e^-)}$	BRs and angular obs. in $b \to s \mu^+ \mu^-$
[BaBar, Belle, LHCb; LHCb'17]	[LHCb, Belle, ATLAS, CMS]
$\sim 2.1 - 2.6\sigma$ (w/ SM)	$\sim 2.2 - 2.9\sigma$ (w/ SM)

Pattern of deviations w.r.t. the SM $\rightarrow$ NP LFUV

Correlation with different flavor sectors

$\Lambda_{NP}^{b\to c,s} \sim \mathcal{O}(1, 100)$ TeV $\Rightarrow$ direct searches,
low-energy precision observables

GIM suppression and CKM suppression:

$$\mathcal{L}_{\rm eff} \supset -\frac{1 - 0.3\,i}{(180\ \mathrm{TeV})^2}(\bar{s}_L\gamma_\mu d_L)(\bar{\nu}_L\gamma^\mu\nu_L) + \mathrm{h.c.}$$

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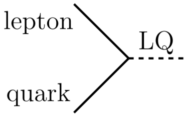
HERE: discuss what can be learned from rare kaon decays
in some specific NP contexts

LQs: couplings to quarks and leptons
$\Rightarrow$ effects in (semi-)leptonic decays,
suppressed effects in $B_s^0 - \bar{B}_s^0$

[Bauer+'15, Medeiros V.+'15, Barbieri+'15, Fajfer+'15]



[talks by Stangl, Iyer, T. You, Greljo, Di Luzio, Nardecchia, Fuentes-Martin, Fajfer, Guadagnoli, Jung, Rodriguez Sanchez, Kirk]

Outline

Experimental overview

Present experimental bounds

$\mathcal{B}_{exp}(K^+ \to \pi^+\nu\bar{\nu}) < 3.35 \times 10^{-10}$ @ 90 % CL [BNL-E787, E949]

$\mathcal{B}_{exp}(K_L \to \pi^0\nu\bar{\nu}) < 2.6 \times 10^{-8}$ @ 90 % CL [KEK-E391a]

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Near/coming future

NA62/CERN: $K^\pm \to \pi^\pm\nu\bar{\nu}$; KOTO/J-PARC: $K_L \to \pi^0\nu\bar{\nu}$ (CPV)

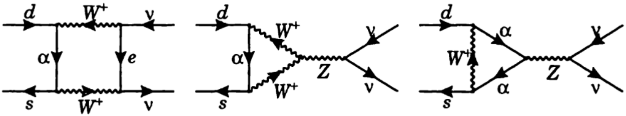
$\mathcal{B}_{exp}(K^+ \to \pi^+\nu\bar{\nu}) < 11 \times 10^{-10}$ @ 90 % CL [NA62, preliminary]

$\mathcal{B}_{exp}(K_L \to \pi^0\nu\bar{\nu}) < 5.1 \times 10^{-8}$ @ 90 % CL [KOTO]

NA62 and KOTO: anticipated accuracies of $\sim 10\%$

Theoretical overview

[talks by Buras, D'Ambrosio]



$$\mathcal{B}_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) =$$

$$\kappa_+ (1 + \Delta_{QED}) \left[\left(\frac{\mathrm{Im}[\lambda_t]}{\lambda_{CKM}^5} X_t \right)^2 + \left(\frac{\mathrm{Re}[\lambda_c]}{\lambda_{CKM}} (P_c^{\mathrm{pert}} + \delta P_{c,u}^{\mathrm{non.\,pert.}}) + \frac{\mathrm{Re}[\lambda_t]}{\lambda_{CKM}^5} X_t \right)^2 \right]$$

$$\mathcal{B}_{SM}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}[\lambda_t]}{\lambda_{CKM}^5} X_t \right)^2, \qquad \lambda_q = V_{qs}^* V_{qd}$$

[Buras'98, Buras+'15]

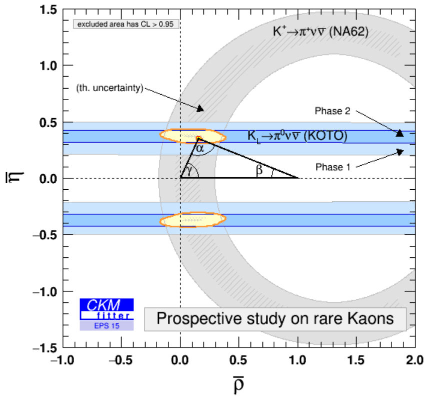
- κ_+, κ_L, non-pert. inputs: semileptonic kaon decays [Mescia+'07]
- X_t: NLO QCD corrections [Buchalla+'93,'99, Misiak+'99]
  NLO electroweak corrections [Brod+'10]
- P_c^{pert}: NNLO QCD corrections [Gorbahn+'04, Buras+'05,'06]
  NLO electroweak corrections [Brod+'08]
- $\delta P_{c,u}^{\mathrm{non.\,pert.}}$ [Isidori+'05]

Impact on the SM

Main uncertainties:

$\mathcal{B}_{SM}(K^\pm)$	$\mathcal{B}_{SM}(K_L)$
$P_c^{\rm pert}$: 5%	$\lvert V_{ub}\rvert$: 3%
$\delta P_{c,u}^{\rm non.\,pert.}$: 3%	γ: 2%
$\lvert V_{cb}\rvert$: 3%	

[CKMfitter, preliminary]



Theoretical predictions in the SM framework

Global fit extraction of $|V_{ub}|$, $|V_{cb}|$, λ, γ: [Ocariz, Camacho, Descotes-Genon]

$\mathcal{B}_{SM}(K^+ \to \pi^+\nu\bar{\nu}) = 0.882^{+0.092}_{-0.098} \times 10^{-10}$ ($\sim$ 10%) [CKMfitter, preliminary]

$\mathcal{B}_{SM}(K_L \to \pi^0\nu\bar{\nu}) = 0.314^{+0.017}_{-0.018} \times 10^{-10}$ ($\sim$ 5%) [CKMfitter, preliminary]

Outline

Structure of LQ contributions to neutral currents

Measurements: R_K/R_K^{SM} and $R_{K^*}/R_{K^*}^{SM} < 1$

Couplings of **scalar** LQs to SM fermions

$SU(3)_C \times SU(2)_L \times U(1)_Y$	down-type quarks	chiral structure	@ tree-level R_K/R_K^{SM}, $R_{K^*}/R_{K^*}^{SM}$
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	$\bar{d}_L^c \nu_L$, $\bar{d}_L^c \ell_L$	$\bar{s}\gamma_\rho P_L b \cdot \bar{\ell}\gamma^\rho P_L \ell$	< 1, < 1
$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$	$\bar{d}_L \ell_R$	$\bar{s}\gamma_\rho P_L b \cdot \bar{\ell}\gamma^\rho P_R \ell$	≈ 1, ≈ 1
$\tilde{R}_2 = (\mathbf{3}, \mathbf{2}, 1/6)$	$\bar{d}_R \ell_L$, $\bar{d}_R \nu_L$	$\bar{s}\gamma_\rho P_R b \cdot \bar{\ell}\gamma^\rho P_L \ell$	< 1, > 1
$\tilde{S}_1 = (\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	$\bar{d}_R^c \ell_R$	$\bar{s}\gamma_\rho P_R b \cdot \bar{\ell}\gamma^\rho P_R \ell$	≈ 1, ≈ 1
$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$\bar{d}_L^c \nu_L$		$= 1$, $= 1$

(w/ ν_R, also $\bar{S}_1 = (\bar{\mathbf{3}}, \mathbf{1}, -2/3)$, and new couplings of $\tilde{R}_2$, S_1)

→ **Tree-level**: S_3

→ Transition $s \to d\nu\bar{\nu}$ @ tree-level: S_3, $\tilde{R}_2$, S_1

LQ contributions to neutral currents

→ Loop-level: other LQs can also imply $R_K/R_K^{SM}, R_{K^*}/R_{K^*}^{SM} < 1$

S_3, R_2, S_1 [Bauer+'15, Bečirević+'16]

→ Sacrifices "elegance" of semi-leptonic effects w/ LQs, but follows structure of the SM

→ Conversely, it may require large couplings

Specific LQ models

$\rightarrow$ In the following, we consider and compare:

- a S_3 model ("Triplet model") [Doršner+'17]
- a R_2 model ("Doublet model") [Bečirević+'16]

$\rightarrow$ **Substantial differences:** $b \rightarrow s\ell\ell$ at different orders

$\rightarrow$ Vector LQs: **renormalizability** requires larger spectrum

[cf. talk by Di Luzio] [Barbieri+'15'16, Buttazzo+'17, Greljo+'17, Fajfer+'16, Bordone+'17]

$\rightarrow$ In the following, focus on correlations w/ $b \rightarrow s\ell\bar{\ell}$, and $b \rightarrow s\nu\bar{\nu}$

R_2 model: features

Interactions with SM fermions:

$$\mathcal{L}^Y_{R_2} = (V_{CKM} \times g_R)_{ij} \bar{u}^i P_R e^j R_2^{5/3} + (g_R)_{ij} \bar{d}^i P_R e^j R_2^{2/3} + (g_L)_{ij} \bar{u}^i P_L \nu^j R_2^{2/3} - (g_L)_{ij} \bar{u}^i P_L e^j R_2^{5/3} + \text{h.c.}$$

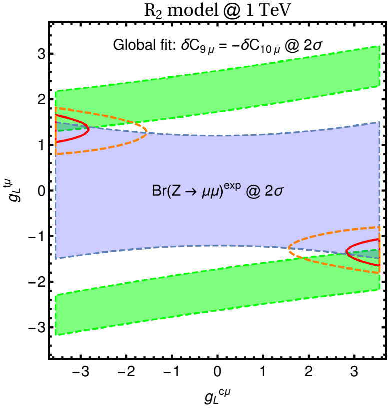
$$g_R = 0_{3\times 3}\,, \qquad g_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & g_L^{c\mu} & g_L^{c\tau} \\ 0 & g_L^{t\mu} & g_L^{t\tau} \end{pmatrix}\,, \qquad m_{R_2}$$

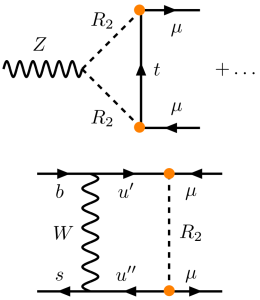
[Bečirević+'17]

- Avoid tree-level contributions to B-decays w/ the *wrong* chirality
- $R_{D^{(*)}}$ not addressed ($g_R^{b\tau} \neq 0$ strongly constrained)
- Consistently avoid first generation couplings
- **No tree-level** contribution to $s \to d\nu\bar{\nu}$

R_2 model: phenomenology

- $g_L^{c\tau} \approx 0$, $g_L^{t\tau} \approx 0$ for large $g_L^{c\mu}$, $g_L^{t\mu}$ due to $\tau \to \mu\gamma$





[Bečirević+'17]

- $(g-2)_\mu$ worsen by $\gtrsim 1\sigma$ (for $g_L^{c\mu}$, $g_L^{t\mu} < \sqrt{4\pi}$)
- Collider bounds: $m_{R_2} \gtrsim 650$ GeV (assuming $t\nu$, $t\tau$ dominate)

S_3 model: features

Interactions with SM fermions:

$$\mathcal{L}^{Y}_{S_3} \equiv -y_{ij}\bar{d}^{C\,i}_{L}\nu^{j}_{L}S_3^{1/3} - (V^{*}_{CKM} \times y)_{ij}\bar{u}^{C\,i}_{L}e^{j}_{L}S_3^{1/3} -\sqrt{2}y_{ij}\bar{d}^{C\,i}_{L}e^{j}_{L}S_3^{4/3} + \sqrt{2}(V^{*}_{CKM} \times y)_{ij}\bar{u}^{C\,i}_{L}\nu^{j}_{L}S_3^{-2/3} + \mathrm{h.c.}$$

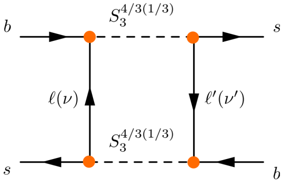
$$y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix}, \quad V^{*}_{CKM} \times y \approx \begin{pmatrix} 0 & \lambda\, y_{s\mu} & \lambda\, y_{s\tau} \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix}, \quad m_{S_3}$$

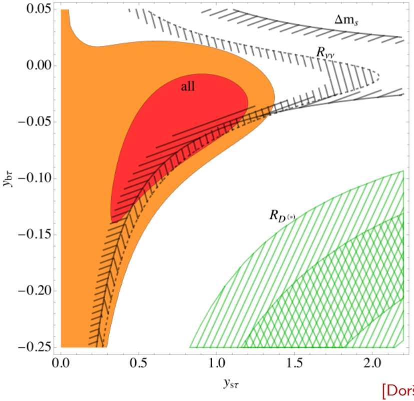
[Doršner+'17]

- Chiral LQ, one single coupling matrix
- With the **choice** $\mathbf{y_{d\mu} = 0 \Rightarrow}$ **no** $\mathbf{s \to d\nu\bar{\nu}}$ @ tree-level

S_3 model: phenomenology

$b \to s\mu^+\mu^-$, $b \to s\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$
at the tree-level





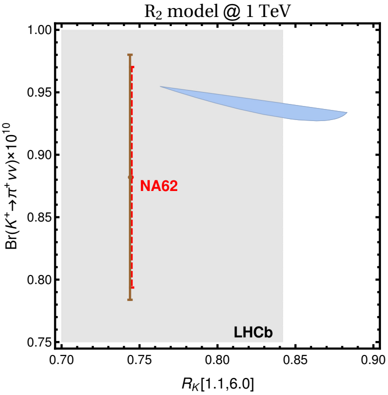
[Doršner+'17]

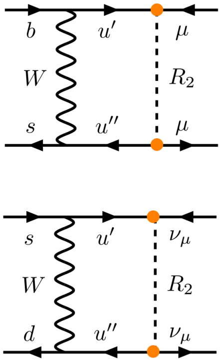
- $R_{\nu\nu}^{(*)} = \frac{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})_{\rm SM}}$, $\Delta m_s(B_s^0\bar{B}_s^0)$
- $R_{D^{(*)}}$ not accommodated
- Collider bounds on LQ pair and $\tau\tau$ production satisfied

Outline

Results for the R_2 model

Effects induced by muon couplings: $\{g_L^{c\mu}, g_L^{t\mu}\}_{1\sigma}$

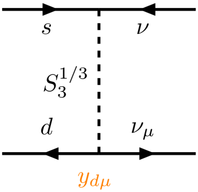




Max. enhancement of 9% for $K^{\pm} \to \pi^{\pm}\nu\bar{\nu}$ and 5% for $K_L \to \pi^0\nu\bar{\nu}$

Results for the S_3 model + $y_{d\mu}$

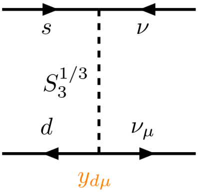
$$y = \begin{pmatrix} 0 & y_{d\mu} & 0 \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix}$$



- Relax the initial requirement of $y_{d\mu} = 0$ (here, real)

Results for the S_3 model $+ y_{d\mu}$

$$y = \begin{pmatrix} 0 & y_{d\mu} & 0 \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix}$$

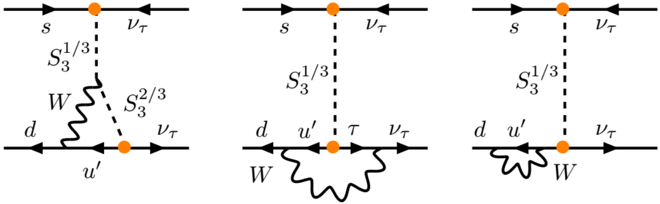


- Relax the initial requirement of $y_{d\mu} = 0$ (here, real)
- The experimental bound of $K^\pm \to \pi^\pm \nu\bar{\nu}$ sets $|y_{d\mu}| \lesssim 3 \times 10^{-4}$
- Much stronger than the **LNV** $\tau \to \mu + K_S^0$ [Davidson+'10]

Results for the S_3 model

- SM: $|V_{td}V_{ts}| \sim \lambda^5$
- $1/\lambda^2$ enhancement

(NP: vertex)
gauge-inv.
combination

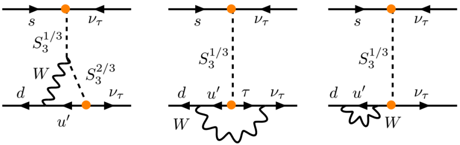


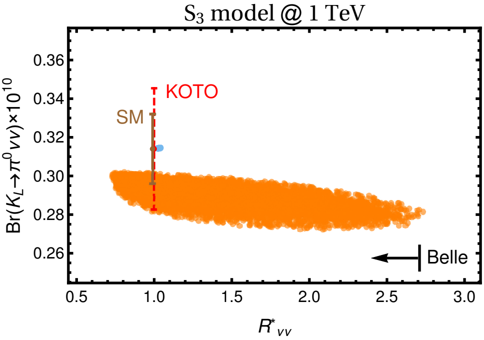
	c	t	cc	$ct,\ tc$	tt
(SM)	$g^4\lambda$	$g^4\lambda^5$			
(NP: vertex)	$g^2\lambda y_{s\tau}^2$	$g^2\lambda^3 y_{s\tau}y_{b\tau}$			
(NP: Box)			$g^2\lambda y_{s\tau}^2$	$g^2\lambda^3 y_{s\tau}y_{b\tau}$	$g^2\lambda^5 y_{b\tau}^2$

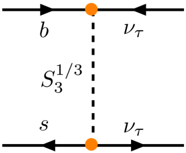
Results for the S_3 model, $y^{\rm tree}_{d\mu} = 0$

tau couplings:

$$y_{d\tau} \stackrel{1\,\rm TeV}{=} [(3.8+1.5i)y_{b\tau} \to -(0.16+0.06i)y_{s\tau}] \times 10^{-4}$$







Max. suppression of 10% for $K^\pm \to \pi^\pm\nu\bar{\nu}$ and 14% for $K_L \to \pi^0\nu\bar{\nu}$

Comparison

Important modulations ($\gtrsim$ theo. unc.) also for $S_1 + S_3$:
suppression of $\sim 24\%$ for $K^\pm \to \pi^\pm\nu\bar{\nu}$, $\sim 34\%$ for $K_L \to \pi^0\nu\bar{\nu}$

[Crivellin+'17]

Comparison

Important modulations ($\gtrsim$ theo. unc.) also for $S_1 + S_3$: suppression of $\sim 24\%$ for $K^\pm \to \pi^\pm\nu\bar{\nu}$, $\sim 34\%$ for $K_L \to \pi^0\nu\bar{\nu}$ [Crivellin+'17]

$(sd)(\ell\ell)$ transitions in the SM: large $\mathcal{B}(K^\pm \to \pi^\pm\ell^+\ell^-)$ points to large long-distance effects from $K \to \pi\gamma^*$

$\to$ The SD from NP do not produce large effects to $(sd)(\ell\ell)$

Conclusion

- B-physics anomalies: perhaps a true guide for extending the SM
- Need other flavor sectors to shape the SM extension
- **Important exp. progress in the coming years in K-physics** & theoretically clean observables
- Correlation among different sectors strongly depends on specific NP model: considered scalar LQs here
- Same couplings in $b \to s\mu^+\mu^-$ and/or $b \to s\nu\bar{\nu}$ also in $s \to d\nu\bar{\nu}$ for the models studied beyond the tree level
- Found modulations of $\sim 10\%$ even for loop contributions

Merci!

Structure of LQ contributions to neutral currents

Couplings of **vector** LQs to SM fermions			
$SU(3)_C \times SU(2)_L \times U(1)_Y$	down-type quarks	chiral structure	@ tree-level R_K/R_K^{SM}, $R_{K^*}/R_{K^*}^{SM}$
$U_3 = (\mathbf{3}, \mathbf{3}, 2/3)$	$\bar{d}_L \nu_L$, $\bar{d}_L \ell_L$	$\bar{s}\gamma_\rho P_L b \cdot \bar{\ell}\gamma^\rho P_L \ell$	< 1, < 1
$V_2 = (\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	$\bar{d}_R^c \nu_L$, $\bar{d}_R^c \ell_L$, $\bar{d}_L^c \ell_R$	$\bar{s}\gamma_\rho P_R b \cdot \bar{\ell}\gamma^\rho P_L \ell$ $\bar{s}\gamma_\rho P_L b \cdot \bar{\ell}\gamma^\rho P_R \ell$	< 1, > 1 ≈ 1, ≈ 1
$\tilde{V}_2 = (\bar{\mathbf{3}}, \mathbf{2}, -\frac{1}{6})$			$= 1$, $= 1$
$\tilde{U}_1 = (\mathbf{3}, \mathbf{1}, 5/3)$			$= 1$, $= 1$
$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$	$\bar{d}_L \ell_L$, $\bar{d}_R \ell_R$	$\bar{s}\gamma_\rho P_L b \cdot \bar{\ell}\gamma^\rho P_L \ell$ $\bar{s}\gamma_\rho P_R b \cdot \bar{\ell}\gamma^\rho P_R \ell$	< 1, < 1 ≈ 1, ≈ 1

(w/ ν_R, also $\bar{U}_1$, $= (\mathbf{3}, \mathbf{1}, -1/3)$, and new couplings of $\tilde{V}_2$)

Couplings of scalar LQs to SM fermions		
LQs	Structures of the couplings	
	down-type	up-type
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	$\bar{d}^c_L \nu_L\,, \bar{d}^c_L \ell_L\,,$	$\bar{u}^c_L \nu_L\,, \bar{u}^c_L \ell_L$
$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$	$\bar{d}_L \ell_R\,,$	$\bar{u}_L \ell_R\,, \bar{u}_R \ell_L\,, \bar{u}_R \nu_L$
$\tilde{R}_2 = (\mathbf{3}, \mathbf{2}, 1/6)$	$\bar{d}_R \ell_L\,, \bar{d}_R \nu_L$	
$\tilde{S}_1 = (\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	$\bar{d}^c_R \ell_R$	
$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$\bar{d}^c_L \nu_L\,,$	$\bar{u}^c_L \ell_L\,, \bar{u}^c_R \ell_R$

Couplings of vector LQs to SM fermions		
LQs	Structures of the couplings	
	down-type	up-type
$U_3 = (\mathbf{3}, \mathbf{3}, 2/3)$	$\bar{d}_L \nu_L \, , \bar{d}_L \ell_L \, ,$	$\bar{u}_L \nu_L \, , \bar{u}_L \ell_L$
$V_2 = (\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	$\bar{d}^c_R \nu_L \, , \bar{d}^c_R \ell_L \, , \bar{d}^c_L \ell_R \, ,$	$\bar{u}^c_L \ell_R$
$\tilde{V}_2 = (\bar{\mathbf{3}}, \mathbf{2}, -1/6)$		$\bar{u}^c_R \ell_L \, , \bar{u}^c_R \nu_L$
$\tilde{U}_1 = (\mathbf{3}, \mathbf{1}, 5/3)$		$\bar{u}_R \ell_R$
$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$	$\bar{d}_L \ell_L \, , \bar{d}_R \ell_R \, ,$	$\bar{u}_L \nu_L$