Footprints of LQs: from B to K rare decays

Luiz Vale Silva

University of Sussex

Nov 1st, 2017

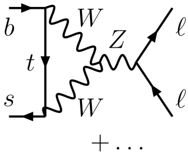
[arXiv:1711.xxxxx [hep-ph]], in collaboration with
Svjetlana Fajfer and Nejc Košnik (Institut Jožef Stefan)

NExT Physics Meting, RHUL

Outline

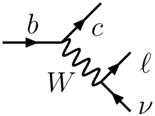
B-physics anomalies

SM LFU (Lepton Flavor Universality) respected to a very good extent
Pattern of deviations w.r.t. the SM $\to$ NP LFUV



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)



Charged Currents

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

Possible EFT interpretations

$$\mathrm{N.C.}: \mathcal{L}^{NP}_{b\to s\ell\ell} \supset 4\frac{G_F}{\sqrt{2}} V_{tb} V^*_{ts} \frac{e^2}{16\pi^2}\left[\delta^\ell\, \bar{s}\gamma_\rho P_L b \cdot \bar{\ell}\gamma^\rho (1-\gamma_5)\ell\right] + \mathrm{h.c.}$$

[Altmannshofer+'17, Capdevila+'17, L.-S. Geng+'17]

$$\mathrm{C.C.}: \mathcal{L}^{NP}_{b\to c\ell\nu} \supset -\tfrac{2G_F}{\sqrt{2}} V_{cb}\left[\epsilon^\ell\, \bar{c}\gamma_\rho P_L b \cdot \bar{\ell}\gamma^\rho (1-\gamma_5)\nu_\ell\right] + \mathrm{h.c.}$$

[X.-Q. Li+'16, Alonso+'16, Celis+'17]

Possible EFT interpretations

$$\text{N.C.} : \mathcal{L}^{NP}_{b\to s\ell\ell} \supset 4\frac{G_F}{\sqrt{2}} V_{tb} V^*_{ts} \frac{e^2}{16\pi^2}\left[\delta^\ell\, \bar{s}\gamma_\rho P_L b \cdot \bar{\ell}\gamma^\rho(1-\gamma_5)\ell\right] + \text{h.c.}$$

[Altmannshofer+'17, Capdevila+'17, L.-S. Geng+'17]

$$\text{C.C.} : \mathcal{L}^{NP}_{b\to c\ell\nu} \supset -\tfrac{2G_F}{\sqrt{2}} V_{cb}\left[\epsilon^\ell\, \bar{c}\gamma_\rho P_L b \cdot \bar{\ell}\gamma^\rho(1-\gamma_5)\nu_\ell\right] + \text{h.c.}$$

[X.-Q. Li+'16, Alonso+'16, Celis+'17]

$\delta^\mu(\mu_b)$ and $\epsilon^\tau(\mu_b)$ at the level of $\sim \mathcal{O}(10\% - 20\%)$ of the SM,

with very different meanings: SM loop vs. SM tree

New degrees of freedom at scales $\Lambda_{NP} \sim \mathcal{O}(1-100)$ TeV

Correlation with other flavor sectors

Move to specific models to relate B- and K-decays [Crivellin+'16, Bordone+'17]

Rare $s \to d\nu\nu$ transitions

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

Collecting data, announcements expected before 202X ($X = 0, 1, 2$)

Correlation with other flavor sectors

Move to specific models to relate B- and K-decays [Crivellin+'16, Bordone+'17]

Rare $s \to d\nu\nu$ transitions

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

Collecting data, announcements expected before 202X (X $= 0, 1, 2$)

HERE: discuss what can be learned from these transitions in some specific NP contexts: leptoquarks (LQs)

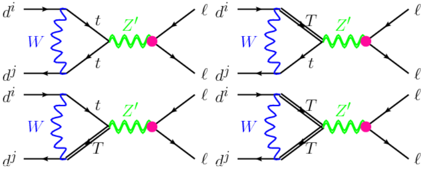
Outline

A few interesting model-building directions:

A few interesting model-building directions:

Z' models

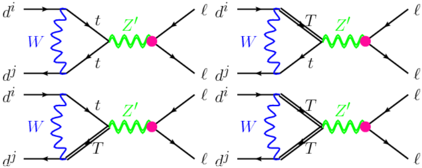
[Altmannshofer+'14, Kamenik+'17,...]



A few interesting model-building directions:

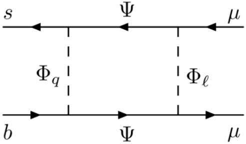
Z' models

[Altmannshofer+'14, Kamenik+'17,...]



New fermions Ψ and scalars Φ

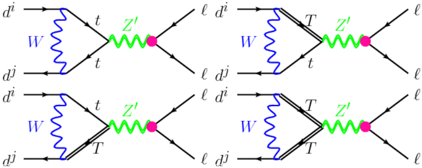
[Gripaios+'15, Arnan+'15]



A few interesting model-building directions:

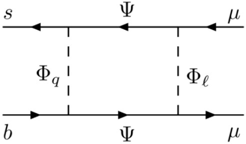
Z' models

[Altmannshofer+'14, Kamenik+'17,...]



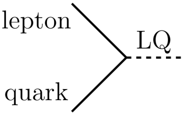
New fermions Ψ and scalars Φ

[Gripaios+'15, Arnan+'15]



LQs: couplings to quarks
and leptons $\Rightarrow$
effects in (semi-)leptonic decays

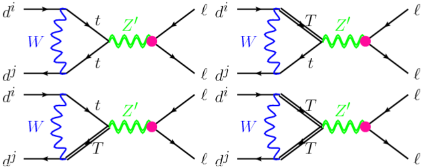
[Hiller+'14,Gripaios+'14,Becirevic+'15'16,M. Varzielas+'15,Fajfer+'15,...]



A few interesting model-building directions:

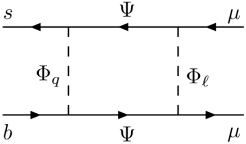
Z' models

[Altmannshofer+'14, Kamenik+'17,...]



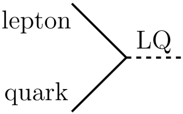
New fermions Ψ and scalars Φ

[Gripaios+'15, Arnan+'15]



LQs: couplings to quarks and leptons $\Rightarrow$ effects in (semi-)leptonic decays

[Hiller+'14,Gripaios+'14,Becirevic+'15'16,M. Varzielas+'15,Fajfer+'15,...]



More generally, **difficult** to accommodate both classes of LFUV anomalies, $R_{K^{(*)}}$ and $R_{D^{(*)}}$, simultaneously

Leptoquark models

- First LQs: matter unification [Pati, Salam '70's; Georgi, Glashow '74,...]

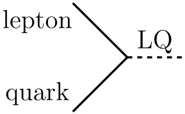
Leptoquark models

- First LQs: matter unification [Pati, Salam '70's; Georgi, Glashow '74,...]
- "phenomenological approach":
  a single (or a set of) LQ for flavor phenomenology,
  e.g., **lightest particle** in a concrete extension

Leptoquark models

- First LQs: matter unification [Pati, Salam '70's; Georgi, Glashow '74,...]
- "phenomenological approach":
  a single (or a set of) LQ for flavor phenomenology,
  e.g., **lightest particle** in a concrete extension
- Spin-0 and spin-1 particle coupling to SM + ν_R d.o.f.,
  gauge invariant, dim. = 4 operators:

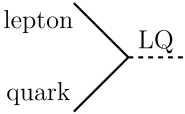
$$\underbrace{S_3, R_2, \tilde{R}_2, \tilde{S}_1, S_1, \bar{S}_1}_{6\,scalar\ LQs},\ \underbrace{U_3, V_2, \tilde{V}_2, \tilde{U}_1, U_1, \bar{U}_1}_{6\,vector\ LQs}$$



Leptoquark models

- First LQs: matter unification [Pati, Salam '70's; Georgi, Glashow '74,...]
- "phenomenological approach":
  a single (or a set of) LQ for flavor phenomenology,
  e.g., **lightest particle** in a concrete extension
- Spin-0 and spin-1 particle coupling to SM + ν_R d.o.f.,
  gauge invariant, dim. = 4 operators:

$$\underbrace{S_3, R_2, \tilde{R}_2, \tilde{S}_1, S_1, \bar{S}_1}_{6\, scalar\ LQs},\ \underbrace{U_3, V_2, \tilde{V}_2, \tilde{U}_1, U_1, \bar{U}_1}_{6\, vector\ LQs}$$



- Vector LQs: **renormalizable** model requires larger spectrum

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			
LQs	down-type interac.	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/ SM $+ \nu_R$, also $\bar{S}_1 = (\bar{\mathbf{3}}, \mathbf{1}, -2/3)$ and new couplings)

$\rightarrow$ Tree-level: S_3

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

Outline

Specific LQ models

→ In the following, we consider and compare:

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

→ Detailed phenomenological studies available

→ **Substantial differences:** e.g., $b \to s\ell\ell$ at different orders

R_2 model: features

Interactions with SM fermions:

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

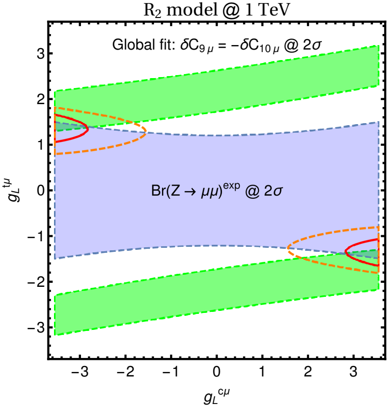
$$g_R = 0_{3\times 3}\,, \qquad g_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & g_L^{c\mu} & g_L^{c\tau} \\ 0 & g_L^{t\mu} & g_L^{t\tau} \end{pmatrix}\,, \qquad m_{R_2}$$

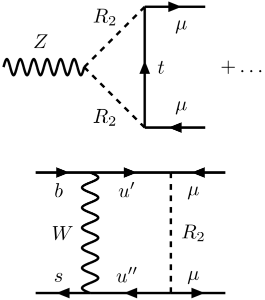
[Becirevic+'17]

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

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 $\tau \to \mu\gamma$





$g_L^{c\mu}$, $g_L^{t\mu} < \sqrt{4\pi}$

- $(g-2)_\mu$ worsen by $\sim 1\sigma$
- Collider bounds: $m_{R_2} \gtrsim 650$ GeV (assuming $t\nu$, $t\tau$ dominate)

S_3 model: features

Interactions with SM fermions:

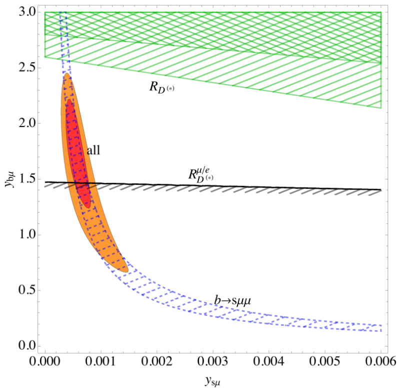
$$\mathcal{L}^{Y}_{S_3} \equiv -y_{ij}\bar{d}^{C\,i}_{L}\nu^{j}_{L}S_3^{1/3} - (V^{*}_{CKM}y)_{ij}\bar{u}^{C\,i}_{L}e^{j}_{L}S_3^{1/3} -\sqrt{2}y_{ij}\bar{d}^{C\,i}_{L}e^{j}_{L}S_3^{4/3} + \sqrt{2}(V^{*}_{CKM}y)_{ij}\bar{u}^{C\,i}_{L}\nu^{j}_{L}S_3^{-2/3} + \text{h.c.}$$

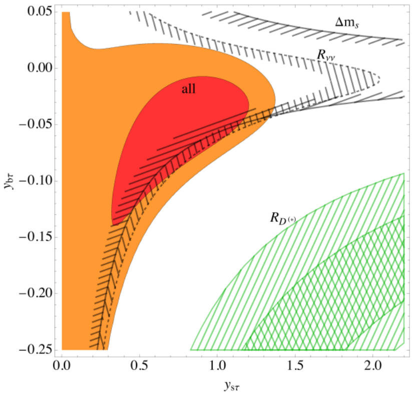
$$y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix}, \quad V^{*}_{CKM}y \approx \begin{pmatrix} 0 & \lambda_{CKM}\, y_{s\mu} & \lambda_{CKM}\, y_{s\tau} \\ 0 & y_{s\mu} & y_{s\tau} \\ 0 & y_{b\mu} & y_{b\tau} \end{pmatrix}, \quad m_{S_3}$$

[Doršner+'17]

- Single coupling matrix for up- and down-type processes
- With the **choice** $\mathbf{y_{d\mu} = 0} \Rightarrow$ no $s \to d\nu\nu$ @ tree-level

S_3 model: phenomenology





[Doršner+'17]

- $R^{\mu/e}_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\mu\nu)}{\mathcal{B}(B \to D^{(*)}e\nu)}$, $R^{(*)}_{\nu\nu} = \frac{\mathcal{B}(B \to K^{(*)}\nu\nu)}{\mathcal{B}(B \to K^{(*)}\nu\nu)_{\rm SM}}$, $\Delta m_s(B^0_s \bar{B}^0_s)$
- Collider bounds on LQ pair and $\tau\tau$ production satisfied

Outline

Overview

Experimental values

$\mathcal{B}_{exp}(K^+ \to \pi^+\nu\bar{\nu}) < 3.35 \times 10^{-10}$ @ 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]

NA62 and KOTO: anticipated accuracies of 10%

Theoretical predictions in the SM

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

(tree- and loop-level observables used in the extraction of V_{CKM})

Overview

Experimental values

$\mathcal{B}_{exp}(K^+ \to \pi^+\nu\bar{\nu}) < 3.35 \times 10^{-10}$ @ 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]

NA62 and KOTO: anticipated accuracies of 10%

Theoretical predictions in the SM

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

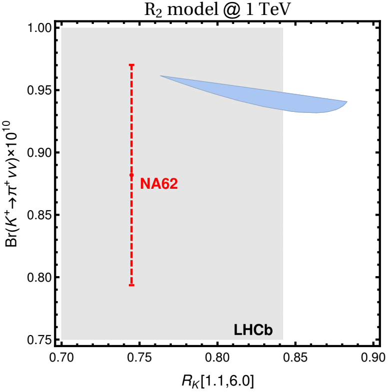
$\mathcal{B}_{SM}(K_L \to \pi^0\nu\bar{\nu}) = 0.314^{+0.017}_{-0.018} \times 10^{-10}$ ($\sim$ 5%) [CKMfitter, preliminary]

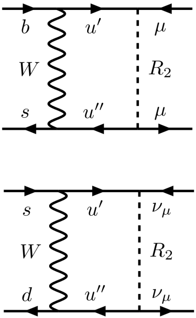
(tree- and loop-level observables used in the extraction of V_{CKM})

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

Results for the R_2 model

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





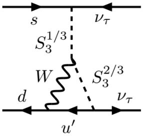
Effects induced by muon couplings, $g_L^{c\mu}, g_L^{t\mu}$

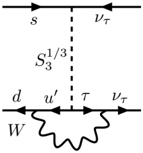
Preliminary results for the S_3 model

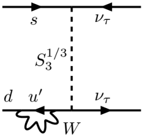
$\sim$ max. suppression of 10% for $K^\pm \to \pi^\pm \nu\nu$ and 14% for $K_L \to \pi^0 \nu\nu$

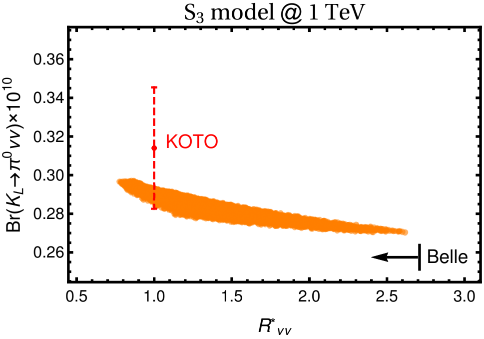
tau couplings:

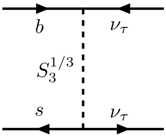
$$y_{d\tau} = [(1.9 + 0.7i)y_{b\tau} - (0.08 + 0.03i)y_{s\tau}] \times 10^{-4}$$











Preliminary: sub-region of $\{g_{s\mu}, g_{b\mu}, g_{s\tau}, g_{b\tau}\}_{1\sigma}$

What do we learn?

To correlate B- and K-physics, two LQ models w/ real couplings:
$R_2 : \{g_L^{c\mu}, g_L^{t\mu}, g_L^{c\tau}, g_L^{t\tau}\}$, $S_3 : \{y_{c\mu}, y_{t\mu}, y_{c\tau}, y_{t\tau}\}$ $\quad (m_{R_2} = m_{S_3} = 1$ TeV$)$

- Given a model: must rely on the **complementarity** of the two channels
- The comparison of R_2 and S_3 illustrates possible ways to **discriminate** models addressing the B-anomalies:

  e.g., suppression/enhancements of $s \to d\nu\nu$
- **Important modulations** ($\gtrsim$ theo. unc.) also for $S_1 + S_3$: suppression of $\sim 24\%$ for $K^\pm \to \pi^\pm\nu\nu$, $\sim 34\%$ for $K_L \to \pi^0\nu\nu$

[Crivellin+'17]

Conclusion

Important exp. progress in the coming years in K-physics

- The specific correlation among B- and K-physics depends on a specific NP model
- LQ models: tentative class of extensions of the SM for interpreting the $b \to s\ell\ell$ anomalies
- The complementary study of $s \to d\nu\nu$ decays may favor a specific LQ models

Thanks!

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
$U_3 = (\mathbf{3}, \mathbf{3}, 2/3)$	$\bar{d}_L \nu_L \, , \bar{d}_L \ell_L \, ,$	$\bar{u}_L \nu_L \, , \bar{u}_L \ell_L$
$V_2 = (\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	$\bar{d}_R^c \nu_L \, , \bar{d}_R^c \ell_L \, , \bar{d}_L^c \ell_R \, ,$	$\bar{u}_L^c \ell_R$
$\tilde{V}_2 = (\bar{\mathbf{3}}, \mathbf{2}, -1/6)$		$\bar{u}_R^c \ell_L \, , \bar{u}_R^c \nu_L$
$\tilde{U}_1 = (\mathbf{3}, \mathbf{1}, 5/3)$		$\bar{u}_R \ell_R$
$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$	$\bar{d}_L \ell_L \, , \bar{d}_R \ell_R \, ,$	$\bar{u}_L \nu_L$

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

- Relax the initial requirement of $y_{d\mu} = 0$
- A real $y_{d\mu}^{\text{tree}}$ saturates the experimental bound of $K^\pm \to \pi^\pm \nu\nu$: $|y_{d\mu}|$ below $\sim 3 \times 10^{-4}$
- Much stronger than $\tau \to \mu + K_S^0$ [Davidson+'10]

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