Is Lepton Flavour Universality Violation a hint on nonunitary New Physics Couplings?

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Motivation

Recent data from LHCb, Belle (and BaBar) experiments suggest violation of **Lepton Flavour Universality** (LFU).
The ratios (to reduce theoretical uncertainties)

$$R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}\,, \quad R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu\mu)}{\mathrm{BR}(B \to K^{(*)}ee)}$$

show tensions with the Standard Model (SM) predictions:

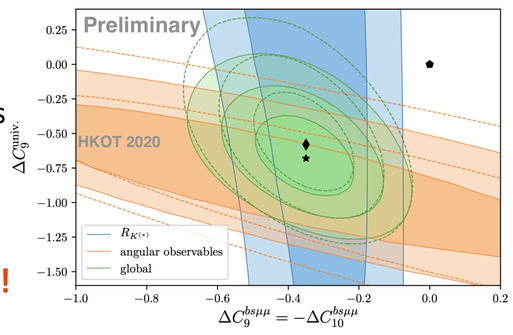
$$R_{K[1.1,6]} = 0.846 \pm^{0.060}_{0.054} \pm^{0.016}_{0.014}\,, \quad R_K^{\mathrm{SM}} = 1.0003 \pm 0.0001 \quad (2.5\sigma)$$
$$R_{K^*[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05\,, \quad R^{\mathrm{SM}}_{K^*[1.1,6]} \sim 0.99 \quad (2.6\sigma)$$

$$R_D = 0.340 \pm 0.027 \pm 0.013\,, \quad R_D^{\mathrm{SM}} = 0.299 \pm 0.003 \quad (1.4\sigma)$$
$$R_{D^*} = 0.295 \pm 0.011 \pm 0.008\,, \quad R_{D^*}^{\mathrm{SM}} = 0.258 \pm 0.005 \quad (2.5\sigma)$$

Many solutions have been proposed!

Effective Field Theory:
- ▶ Model independent fit
  - ⇝ **correlations** between observables

⇒ **Identify viable SM extensions to explain LFUV**

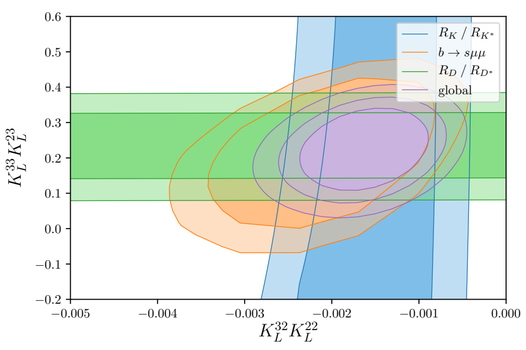


An appealing candidate: **Leptoquarks!**
- ▶ **Single mediator** solution to both $R_{K^{(*)}}$ & $R_{D^{(*)}}$ ⇝ $V_1 \sim (3, 1, -\frac{2}{3})$

★ **Leptoquarks (LQ):** scalar or vector bosons coupling leptons to quarks

Setup: vector leptoquark V_1

Consider a **new massive gauge boson** V_1, naturally embedded in $SU(4)_C$.
Gauge couplings are strictly **universal;** how to explain **LFU violation?**
- ▶ Only V_1 with a universal gauge coupling cannot explain the data...
  (And data strongly favours nonuniversal LQ couplings!)
  - ⇒ **Nonuniversal** couplings needed! How can this be achieved?



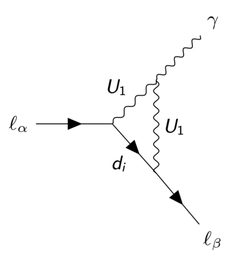
Note: For simplicity, we neglect right-handed couplings of the LQ.

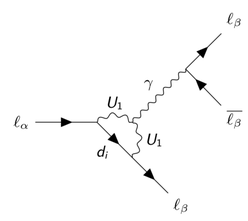
- ▶ Add n **vector-like** (VL) leptons mixing with (left-handed) SM leptons
  - ⇒ effective LQ-q-ℓ couplings $K_L^{q\ell}$ parametrised via **non-unitary matrix** (from mixing with heavy states)
  - ⇒ Induce **LFUV structure** in $C_{9,10}^{ij;\ell\ell'}$ **Wilson coefficients:**

$$C_{9,10}^{ij;\ell\ell'} = \mp \frac{\pi}{\sqrt{2}G_F\,\alpha\,V_{3j}\,V_{3i}^*}\,\frac{1}{m_U^2}\,K_L^{i\ell'}\,K_L^{j\ell *}$$

Phenomenological Constraints

Flavour observables (**tree** & loop level):
- **Meson decays:** $K_L \to e^\pm\mu^\mp$, $B^0_{d,s} \to \ell_i^\pm \ell_j^\mp$ ...
- **cLFV:** $\ell \to \ell'\gamma$, $\ell \to \bar{\ell}'\ell'\ell'$, $\mu - e$ conversion, ...
- **Precision Observables:** $Z \to \ell\ell$, $\Gamma(Z \to \mu\mu)/\Gamma(Z \to ee)$, ...
- **Further constraints:** $B_s \to \mu^+\mu^-$, ...
- **Collider searches:** ATLAS and CMS (LHC)





Tight constraints on free parameters:
- LQ mass: $R_{D^{(*)}} \Rightarrow m_U \sim 1.5 - 3\,\mathrm{TeV}$
- $3+$? mixing angles and $1+$? phases, depending on number of VL generations

References

[1] C. Hati, JK, J. Orloff, A. M. Teixeira: [JHEP12(2019)006].

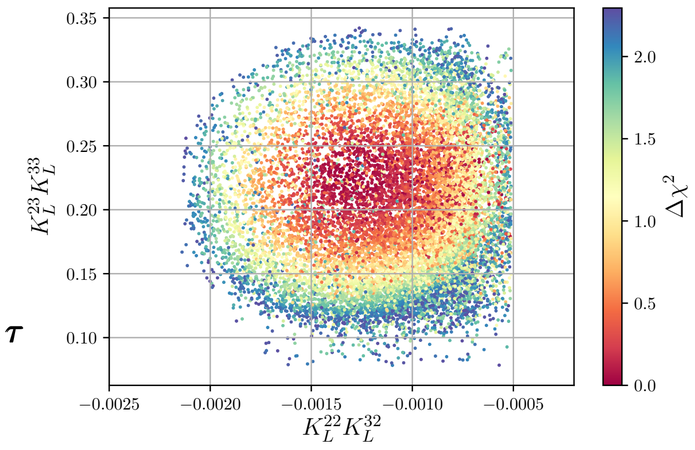
Results

Tightest constraints on parameter space from combination of **LFV processes:**
$K_L \to e^\pm\mu^\mp$, $(\mu - e)$ **conversion and** $\ell \to \ell'\gamma$

⇒ $n = 1$ **VL** (heavy) leptons: excluded by **flavour observables** ✗

⇒ Consider $n = 3$ **generations of VL leptons!**

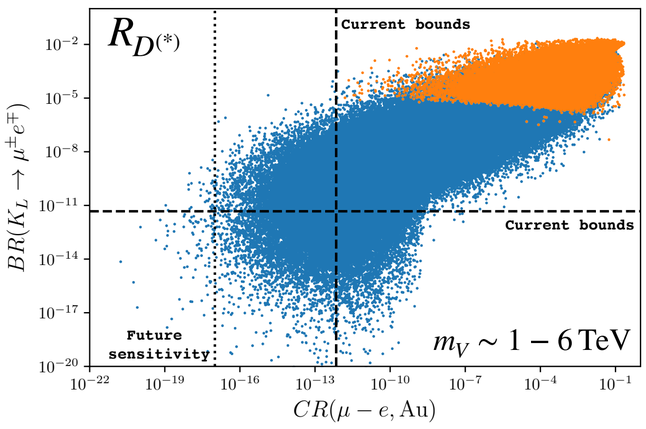
Numerical analysis:
scan over $12\,\theta_{ij}$, $m_U = 1.5$ TeV
- 1σ range around best fit: **compatible with LFV bounds!**
- coloured **ellipse** ⇝ **NP** predominantly coupled to μ & τ



Effective coupling matrix is highly **nonunitary** !

Depending on $SU(2)_L$ **representation of VL** leptons (isosinglets vs isodoublets):
⇒ Potential **modification of** $Z - \ell - \ell$ **couplings**
Excessive contributions to $\Gamma(Z \to \ell\ell)$ **and** $\Gamma(Z \to \ell\ell')$

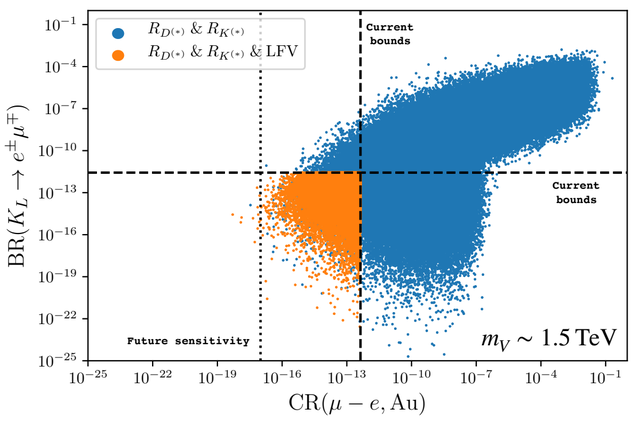
(A) Heavy vector-like $SU(2)_L$-singlets:



- Compatible (3σ) with $R_{D^{(*)}}$
- Compatible with Z-decays

⇒ **Nonunitarity** driven by $R_{D^{(*)}}$
⇒ Full parameter space **excluded** by Z- and/or **LFV constraints!** ✗ ✗

(B) Heavy vector-like $SU(2)_L$-doublets:



- Compatible (3σ) with $R_{D^{(*)}}$ & $R_{K^{(*)}}$
- Compatible with **LFV bounds** and $R_{D^{(*)}}$ & $R_{K^{(*)}}$ at 1σ!

⇒ **Future LFV** experiments (e.g. COMET, Mu2e) will probe most of the parameter space!

⇒ recover **universality of** $Z - \ell - \ell$ **couplings**
⇒ Explain $R_{K^{(*)}}$, $R_{D^{(*)}}$ & comply with all **phenomenological constraints** ✓ ✓ ✓

Conclusions

$SU(2)_L$**-singlet vector leptoquark:** successful **single mediator** solution to accommodate both B**-meson decay** anomalies

(i) Account for $R_{K^{(*)}}$ & $R_{D^{(*)}}$
(ii) Comply with bounds on **LFV**
⇒ **nonunitary** couplings to SM fermions (source of **nonuniversal** Z **decays!**)

The results of our study [1] allow to:
- **falsify classes of UV-complete frameworks**
  - V_1 + a single heavy vector-like lepton generation ✗
  - $V_1 + n \geq 2$ generations of $SU(2)_L$-singlet heavy vector-like leptons ✗
- **identify viable scenarios** to explain $R_{K^{(*)}}$ & $R_{D^{(*)}}$
  $V_1 + n \geq 2$ $SU(2)_L$-doublet heavy **VL leptons**,
  in agreement with *all constraints !!!* ✓ ✓ ✓