# $B$-Physics Anomalies in the Context of Leptoquarks and Flavor Models

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# Motivation

- Experimental data shows several anomalies in $B$-decays
  - $R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B}\to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(\bar{B}\to D^{(*)}l\bar{\nu})}$ ($3.9\sigma$, BaBar, Belle, LHCb)
  - $R_K = \frac{\mathcal{B}(\bar{B}\to \bar{K}\mu^+\mu^-)}{\mathcal{B}(\bar{B}\to \bar{K}e^+e^-)}$ ($2.6\sigma$, LHCb)
- Anomalies involve leptons and quarks
  $\Rightarrow$ Obvious approach: Leptoquark models
- Anomalies hint at lepton non-universality
  $\Rightarrow$ Satisfying explanation requires a model of flavor

$\Rightarrow$ Study leptoquarks in flavor models

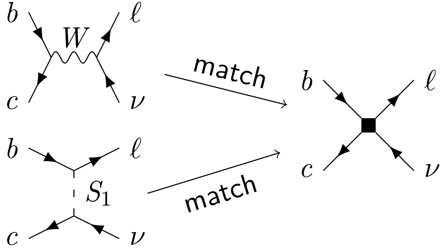
# Effective field theory

Heavy degrees of freedom are removed from the theory.
$\Rightarrow$ Framework for bottom-up approach

## Effective Hamiltonian

$$\mathcal{H}_{\text{eff}}^{(6)} = \frac{1}{\Lambda^2} \sum_i C_i \mathcal{O}_i$$

- Wilson coefficients $C_i$:
  High energy realm
- Effective operators $\mathcal{O}_i$:
  Low energy realm



# EFT for $b \to c\ell\bar{\nu}$ transitions

## Effective Hamiltonian

$$\mathcal{H}_{\text{eff}}^{b\to c\ell\bar{\nu}} = \frac{4G_{\text{F}}}{\sqrt{2}} V_{cb} \left( \delta_{\ell\nu} \mathcal{O}_{V_1}^{\ell\nu} + \sum_i C_i^{\ell\nu} \mathcal{O}_i^{\ell\nu} \right)$$

## Dimension-6 Operators

$$\begin{aligned}
\mathcal{O}_{V_{1(2)}}^{\ell\nu} &= \left[\bar{c}_{L(R)} \gamma^{\mu} b_{L(R)}\right] \left[\bar{\ell}_L \gamma_{\mu} \nu_L\right] \\
\mathcal{O}_{S_{1(2)}}^{\ell\nu} &= \left[\bar{c}_{L(R)} b_{R(L)}\right] \left[\bar{\ell}_R \nu_L\right] \\
\mathcal{O}_{T}^{\ell\nu} &= \left[\bar{c}_R \sigma^{\mu\nu} b_L\right] \left[\bar{\ell}_R \sigma_{\mu\nu} \nu_L\right]
\end{aligned}$$

# $R_D$ and $R_{D^*}$

$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(\bar{B} \to D^{(*)}l\bar{\nu})} = \frac{f^{(*)}\left(\langle D^{(*)}|\bar{c}\Gamma_i b|\bar{B}\rangle\,, C_i^{\tau\nu}, m_\tau\right)}{f^{(*)}\left(\langle D^{(*)}|\bar{c}\Gamma_i b|\bar{B}\rangle\,, C_i^{l\nu}, m_l\right)}$$

Experimental data shows a deviation of $3.9\sigma$ from the SM.
Shift of similar size in $R_D$ and $R_{D^*}$:

$$\frac{R_D^{\mathrm{Exp}}}{R_D^{\mathrm{SM}}} \sim \frac{R_{D^{(*)}}^{\mathrm{Exp}}}{R_{D^{(*)}}^{\mathrm{SM}}} \sim 1.3$$

HFAG; Fajfer, Kamenik, Mescia, Nisandzic

Simple case: NP only in $C_{V_1}$

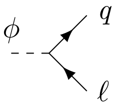
$$\Rightarrow \frac{R_{D^{(*)}}^{\mathrm{Exp}}}{R_{D^{(*)}}^{\mathrm{SM}}} = \frac{\sum_\nu |\delta_{\tau\nu} + C_{V_1}^{\tau\nu}|^2}{\sum_\nu |\delta_{l\nu} + C_{V_1}^{l\nu}|^2}$$

$C_{V_1}$ can account for both deviations in a 'natural' manner.

# Leptoquark models

Schematically:

$$\mathcal{L}_{\mathrm{LQ}} \sim g_{ij}\bar{q}^i \ell^j \phi$$




- Leptoquark $\phi$ couples to quarks and leptons
- Coupling $g$: $3 \times 3$ matrix in flavor space
  $\Rightarrow$ Contributions to various sectors

Charm FCNCs $\rightarrow$ G. Hiller's talk

$$g = \begin{pmatrix} g_{11} & g_{12} & g_{13} \\ g_{21} & g_{22} & g_{23} \\ g_{31} & g_{32} & g_{33} \end{pmatrix}$$

$R_{D^{(*)}}$

$R_K$

# Leptoquark models II

Various LQs have been investigated by several groups:

$$\mathcal{L}_{\rm LQ} = (g_{1\rm L}\,\bar{Q}_L^c i\sigma_2 L_L + g_{1\rm R}\,\bar{u}_R^c e_R)S_1^\dagger \text{ [1,3]}$$
$$+ (h_{1\rm L}\,\bar{Q}_L\gamma^\mu L_L + h_{1\rm R}\,\bar{d}_R\gamma^\mu e_R)\,V_{1\mu}^\dagger \text{ [2]}$$
$$+ g_{3\rm L}\,\bar{Q}_L^c i\sigma_2\vec{\sigma}L_L\vec{S}_3^\dagger \text{ [1,2]} + h_{3\rm L}\,\bar{Q}_L^c\gamma^\mu\vec{\sigma}L_L\,\vec{V}_{3\mu}^\dagger \text{ [4]}$$
$$+ \ldots$$

see Buchmüller et al. (Phys. Lett. B, 191)


[1] Ligeti et al. (arXiv:1506.08896)

[2] Crivellin et al. (arXiv:1506.02661

[3] Bauer et al. (arXiv:1511.01900)

[4] Fajfer et al. (arXiv:1511.06024)


$\Rightarrow C_{V_1}^{\ell\nu} \sim g_{\rm L}^{b\nu}g_{\rm L}^{c\ell}$ or $g_{\rm L}^{b\ell}g_{\rm L}^{c\nu}$ (resp. $h_{\rm L}^{b\nu}h_{\rm L}^{c\ell}$ or $h_{\rm L}^{b\ell}h_{\rm L}^{c\nu}$)
Works for LQs at the TeV-scale with $\mathcal{O}(1)$ couplings

- $S_1$ with $g_{1L}$ only: Strong constraints from $b \to s\bar{\nu}\nu$
- $V_1$ with $h_{1L}$ only: No constraints from $b \to s\bar{\nu}\nu$, additionally: $b \to s\ell^+\ell^-$ @ tree-level $\to R_K$
- $\mathrm{SU}(2)_L$-triplets: More complicated, contributions to $b \to s\bar{\nu}\nu$ and $b \to s\ell^+\ell^-$

# Leptoquarks in flavor basis vs. mass basis

In the flavor basis:

$$\mathcal{L}_{\mathrm{LQ}}^{\mathrm{flavor}} = g_{1\mathrm{L}}\,\bar{Q}_L^c i\sigma_2 L_L S_1^\dagger = g_{1\mathrm{L}}(\bar{u}_L^c e_L - \bar{d}_L^c \nu_L) S_1^\dagger$$

Transformation into mass basis via unitary matrices:

$$d_L \to U_d d_L, \quad u_L \to U_u u_L, \quad e_L \to U_e e_L, \quad \nu_L \to U_\nu \nu_L$$

$\Rightarrow$ Consequences for the LQ couplings $g_{1\mathrm{L}}$:

$$g_{1\mathrm{L}} \to \begin{cases} U_u^{\mathrm{T}} g_{1\mathrm{L}} U_e, & \text{for coupling to } u\text{-type quarks} \\ U_d^{\mathrm{T}} g_{1\mathrm{L}} U_\nu, & \text{for coupling to } d\text{-type quarks} \end{cases}$$

# Flavor models

Goal: Model masses and mixing of quarks and leptons

$$V_{\mathrm{CKM}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

General approach: Modification of Yukawa interactions

$$\mathcal{L}_{\mathrm{mass}} = Y_{ij} H \bar{\psi}_L^i \psi_R^j$$

- Introduce flavon field $\theta$ with VEV $\frac{\langle\theta\rangle}{\Lambda} \sim \lambda \sim 0.2$
- Replace hierarchical Yukawa couplings with $\mathcal{O}(1)$ couplings
- Use a flavor symmetry and appropriate charges to generate the desired structure by multiple insertions of the flavon field

$$\mathcal{L}_{\mathrm{mass}} = Y'_{ij} \left(\frac{\theta}{\Lambda}\right)^{n_{ij}} H \bar{\psi}_L^i \psi_R^j$$

e.g. $\mathrm{U}(1)_{\mathrm{FN}}$-symmetry with charges: $\{\theta\} = -1$, $\{Q_L^{1,2,3}\} = 4, 2, 0$ and $\{\bar{d}_R^{1,2,3}\} = 2, 1, 0$ Froggatt and Nielsen (Nucl. Phys. B147, 1979)

# Flavor models II

$$U_{\mathrm{PMNS}}^{(\mathrm{TBM})} = \begin{pmatrix} \sqrt{2/3} & -\sqrt{1/3} & 0 \\ \sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ \sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

Non-hierarchical mixing in the lepton sector can be naturally obtained from discrete flavor symmetries: e.g. $A_4$-based flavor models Altarelli, Feruglio (arXiv:hep-ph/0504165)

- Assign different representations of $A_4$ to the fields
- Flavon fields $\phi_l$ and $\phi_\nu$ ($A_4$ triplets) with different VEVs in special directions $(1, 0, 0)$ and $(1, 1, 1)$

# Consequences for LQ models

Flavor models give rise to patterns for LQ couplings:

$$g \sim \begin{pmatrix} 0 & 0 & \lambda^4 \\ 0 & 0 & \lambda^2 \\ 0 & 0 & 1 \end{pmatrix} \text{ or } \begin{pmatrix} 0 & \lambda^4 & 0 \\ 0 & \lambda^2 & 0 \\ 0 & 1 & 0 \end{pmatrix} \text{ or } \begin{pmatrix} \lambda^4 & 0 & 0 \\ \lambda^2 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

Isolation of a single lepton generation depending on $A_4$ representation of LQ Hiller and de Medeiros Varzielas (arXiv:1503.01084)

Charm FCNCs → G. Hiller's talk

$$g = \begin{pmatrix} g_{11} & g_{12} & g_{13} \\ g_{21} & g_{22} & g_{23} \\ g_{31} & g_{32} & g_{33} \end{pmatrix}$$

$R_{D^{(*)}}$

$R_K$

⇒ Correlations between different flavor sectors

# Summary

- Experimental data shows anomalies in $B$-decays that hint at lepton non-universality: $R_{D^{(*)}}$, $R_K$, ...
- Possible NP scenarios can be identified through model-independent analysis within EFT (bottom-up approach)
  $\Rightarrow$ Obvious/popular scenarios: Leptoquark models
- Flavor models are neccessary for a satisfying explanation of the anomalies
  $\Rightarrow$ Additional structure for NP model
  $\Rightarrow$ Predictions for observables in other flavor sectors