Leptoquark Flavor Patterns and B Decay Anomalies

Dennis Loose

TU Dortmund

based on arXiv:1609.08895 with Gudrun Hiller and Kay Schönwald

LFV/LFUV Workshop
Paris, 9. November 2016

Motivation

- Experimental data shows several anomalies in B-decays
  - $R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B}\to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(\bar{B}\to D^{(*)}l\bar{\nu})}$ (3.9σ, [BaBar, Belle, LHCb])
  - $R_K = \frac{\mathcal{B}(\bar{B}\to \bar{K}\mu^+\mu^-)}{\mathcal{B}(\bar{B}\to \bar{K}e^+e^-)}$ (2.6σ, [LHCb])
- Anomalies involve leptons and quarks
  $\Rightarrow$ Popular approach: Leptoquark models
  [Bečirević, Fajfer, Košnik et al. + many more]
- Anomalies hint at lepton non-universality and involve various quark flavors
  $\Rightarrow$ Satisfying explanation requires a model of flavor

$\Rightarrow$ Study leptoquarks in flavor models

Leptoquark models

Schematically:

$$\mathcal{L}_{\text{LQ}} \sim Y \bar{Q} L \varDelta$$
$$\Rightarrow \mathcal{L}_{\text{eff}} \supset \frac{Y Y^*}{M_\varDelta^2} [\bar{Q} \varGamma Q] [\bar{L} \varGamma L]$$

- Leptoquark $\varDelta$ couples to quarks and leptons
- Coupling Y: 3×3 matrix in flavor space
  columns $\rightarrow$ lepton gen., rows $\rightarrow$ quark gen.

  $\Rightarrow$ Contributions to various sectors
  (depends on the explicit LQ model)

Charm FCNCs, Kaon decays, ...

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

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

R_K

Flavor models

Goal Model (hierarchies of) masses and mixing of quarks and leptons

Approach Modification of Yukawa interactions

$$\mathcal{L}_{\text{mass}} = -y_{ij} H \bar{\psi}_L^i \psi_R^j$$

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

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

Froggatt–Nielsen-Mechanism

$$\mathcal{L}_{\text{mass}} = -\underbrace{y'_{ij}\left(\frac{\theta}{\Lambda}\right)^{q(\bar{\psi}^i_L)+q(\psi^j_R)}}_{y_{ij}} H\bar{\psi}^i_L\psi^j_R$$

Introduce $U(1)_{\text{FN}}$-symmetry and assign the following charges:

- $q(\theta) = -1$
- $q(\bar{Q}) = q(U) = (4, 2, 0), \quad q(D) = (3, 2, 2)$

$\Rightarrow$ Quark masses and mixing

Works well for hierarchical structures

[Froggatt and Nielsen (Nucl. Phys. B147, 1979)]

A_4-based flavor models

Successful models for non-hierarchical structures (PMNS) are based on discrete, non-abelian subgroups of SU(3)

Representations of A_4:

- Three singlets: $1, 1'$ and $1''$ which form a Z_3
- One triplet with multiplication rules

$$\begin{aligned}(AB)_1 &= a_1b_1 + a_2b_2 + a_3b_3 \\ (AB)_{1'} &= a_1b_2 + a_2b_1 + a_3b_3 \\ (AB)_{1''} &= a_1b_3 + a_2b_2 + a_3b_1\end{aligned}$$

$A_4 \times Z_3 \times U(1)$ model

	L	e_R	μ_R	τ_R	ϕ_ℓ	ϕ_ν	ξ	ξ'
A_4	3	1	$1'$	$1''$	3	3	1	$1'$
Z_3	1	1	1	1	0	2	2	2

VEVs: $\langle\phi_\ell\rangle/\Lambda = c_\ell(1,0,0)$, $\langle\phi_\nu\rangle/\Lambda = c_\nu(1,1,1)$, $\langle\xi^{(\prime)}\rangle/\Lambda = \kappa^{(\prime)}$,
where $c_{\ell,\nu}, \kappa^{(\prime)} \lesssim \lambda^{\text{few}}$

Neutrino mixing (TBM + correction for θ_{13} by ξ'):

$$w_\nu = y[L\nu^c]h_u + \left(x_A\xi + x'_A\xi'\right)[\nu^c\nu^c] + x_B[\phi_\nu\nu^c\nu^c]$$

Diagonal mass matrix for charged leptons:

$$w_L = \frac{y_e}{\Lambda^3}\theta^4[\phi_\ell L]e^c h_d + \frac{y_\mu}{\Lambda^2}\theta^2[\phi_\ell L]'\mu^c h_d + \frac{y_\tau}{\Lambda}[\phi_\ell L]''\tau^c h_d$$

Hierarchy from FN charges $q(E) = (4,2,0)$, $\quad q(L) = 0$

[Altarelli, Feruglio (arXiv:hep-ph/0504165), Varzielas, Pidt (arXiv:1211.5370)]

Resulting patterns for the leptoquark couplings

Assumptions:

- Quarks are trivial singlets of $A_4 \times Z_3$
- Leptoquark Δ is a (non-)trivial singlet of A_4 and carries no FN charge

Consequences of the $A_4 \times Z_3$ structure at leading order:

- Isolation of lepton generations – e.g. if $[\Delta]_{A_4} = 1''$

  $$\mathcal{L}_{\mathrm{LQ}} \supset \bar{Q}[\phi_\ell L]'\Delta \quad \text{or} \quad \bar{Q}\mu_{\mathrm{R}}\Delta$$

  isolates muons
- Couplings to lepton doublets are suppressed relative to the singlet couplings by one VEV
- Non-vanishing Z_3 charges of Δ have to be compensated by additional flavon insertions $(\phi_\nu, \kappa^{(\prime)})$
  $\Rightarrow$ Isolation of two generations via κ and κ' (lepton singlets)
  $\Rightarrow$ Democratic patterns (doublets and singlets)

Resulting patterns for the leptoquark couplings II

Consequences of the $U(1)_{\text{FN}}$ charges:

- Rows of LQ coupling matrices are suppressed by the FN charges of the quarks
- Lepton singlets are also charged under $U(1)_{\text{FN}}$
  $\Rightarrow$ Interference of quark and lepton FN charges in couplings
  $\Rightarrow$ Cancellations are possible

Examples for $[\Delta]_{A_4} = 1''$

$$Y_{\bar{Q}L} \sim Y_{QL} \sim \begin{pmatrix} 0 & c_\ell\lambda^4 & 0 \\ 0 & c_\ell\lambda^2 & 0 \\ 0 & c_\ell\lambda^0 & 0 \end{pmatrix} \equiv L_\mu(\bar{Q}L) = L_\mu(QL)$$

$$Y_{\bar{Q}E} \sim \begin{pmatrix} 0 & \lambda^6 & 0 \\ 0 & \lambda^4 & 0 \\ 0 & \lambda^2 & 0 \end{pmatrix} \equiv R_\mu(\bar{Q}E), \quad Y_{QE} \sim \begin{pmatrix} 0 & \lambda^2 & 0 \\ 0 & \lambda^0 & 0 \\ 0 & \lambda^2 & 0 \end{pmatrix} \equiv R_\mu(QE)$$

Mass basis rotations and higher order corrections

- LQ couplings are defined in the flavor basis
  $\Rightarrow$ Mass basis rotations are necessary

- Hierarchies of the rotation matrices are dictated by the flavor symmetry
  - Quark rotations preserve the hierarchies in the LQ couplings
  - Lepton mass matrix is diagonal at LO, neutrinos are inclusively reconstructed in experiments

- Higher order flavon corrections induce additional effects
  - "0"s are filled in with entries of $\mathcal{O}(\delta)$ (two VEVs), amended by FN charges of quarks and leptons
  - "0"s in R-patterns can be filled in with entries $\sim \mathcal{O}(\delta')$ (three VEVs), which can be larger than the the former corrections if there are cancellations between FN charges

Quarks in non-trivial representations of A_4

- Assigning individual quark generations to non-trivial singlet representations of A_4 provides additional possibilities
- Flavon insertions are necessary to preserve A_4 invariance of the mass terms
  $\Rightarrow$ Z_3 and FN charges have to be adjusted accordingly
  $\Rightarrow$ Mixing of patterns for the respective rows
  $\Rightarrow$ NLO corrections and rotations become more complicated

Example: $\left[\bar{Q}_2\right]_{A_4} = [\varDelta]_{A_4} = 1'' \quad (\theta^2 H \bar{Q}_2 D \to \xi' H \bar{Q}_2 D)$

$$\Rightarrow L_\mu(\bar{Q}L) = \begin{pmatrix} 0 & c_\ell \lambda^4 & 0 \\ 0 & c_\ell \lambda^2 & 0 \\ 0 & c_\ell \lambda^0 & 0 \end{pmatrix} \to \tilde{L}_\mu(\bar{Q}L) = \begin{pmatrix} 0 & c_\ell \lambda^4 & 0 \\ c_\nu & c_\nu & c_\nu \\ 0 & c_\ell \lambda^0 & 0 \end{pmatrix}$$

Phenomenologically viable patterns

Maximal effects in $R_{D^{(*)}}$ are achieved with modified τ-isolation patterns:

- $\tilde{L}_\tau(\bar{Q}L) \sim \begin{pmatrix} \lambda^2 c_\nu & \lambda^2 c_\nu & \lambda^2 c_\nu \\ c_\nu & c_\nu & c_\nu \\ \lambda^2 c_\nu + \delta c_\ell & \lambda^2 c_\nu + \delta c_\ell & c_\ell \end{pmatrix}$

- Similar pattern: $L_\tau(\bar{U}L)$ (additional suppression $c_\nu \to c_\nu \kappa$)

- $R_\tau(AE) \sim \begin{pmatrix} \delta^{(\prime)} * & \delta^{(\prime)} * & \lambda^{q(A_1)} \\ \delta^{(\prime)} * & \delta^{(\prime)} * & \lambda^{q(A_2)} \\ \delta^{(\prime)} * & \delta^{(\prime)} * & \lambda^{q(A_3)} \end{pmatrix}$

  Entries "$*$" are powers of λ and can become large if there are cancellations of FN charges

$\Rightarrow$ LL-contributions suppressed by at least two VEVs, chirality-flipping contributions require only one flavon insertion

Experimental bounds

The strongest constraints arise from:

- LFV Kaon processes $s \to de\mu$
- $B \to K\nu\nu$
- $\mu - e$-conversion in nuclei

Kaon decays, $\mu - e$-conversion

$$\tilde{L}_\tau \sim \begin{pmatrix} \lambda^2 c_\nu & \lambda^2 c_\nu & \lambda^2 c_\nu \\ c_\nu & c_\nu & c_\nu \\ * & * & c_\ell \end{pmatrix}$$

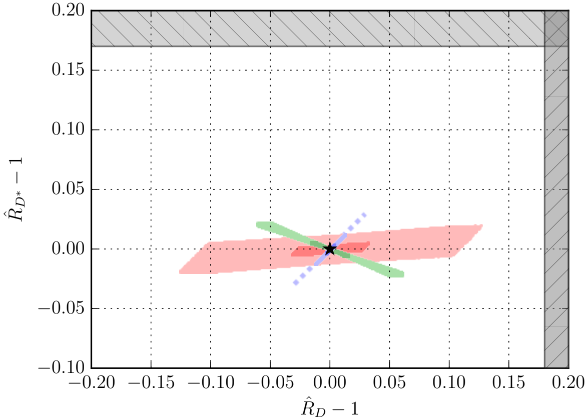
$R_{D^{(*)}}$

$B \to K\nu\nu$

$\Rightarrow$ Strong bounds on c_ν
$\Rightarrow$ Small effects in $R_{D^{(*)}}$

Leptoquark effects in $R_{D^{(*)}}$

$$\mathcal{L}_{\rm LQ} \supset \left(Y_{\bar{U}L}\bar{u}_{\rm R}L_{\rm L} + Y_{\bar{Q}E}\bar{Q}_{\rm L}i\sigma_2 e_{\rm R}\right) S_2^\dagger + \left(Y_{\bar{Q}L}\bar{Q}_{\rm L}\gamma_\mu L_{\rm L} + Y_{\bar{D}E}\bar{d}_{\rm R}\gamma_\mu e_{\rm R}\right) V_1^{\mu\dagger} + Y_{\bar{Q}L}\bar{Q}_{\rm L}\gamma_\mu\vec{\sigma}L_{\rm L}\vec{V}_3^{\mu\dagger}$$



Leptoquark effects in $b \to s\ell\ell$

$$\mathcal{L}_{\rm LQ} \supset Y_{QL}\bar{Q}^c_{\rm L} i\sigma_2 \vec{\sigma} L_{\rm L} \vec{S}_3^\dagger + Y_{\bar{Q}L}\bar{Q}_{\rm L}\gamma_\mu \vec{\sigma} L_{\rm L} \vec{V}_3^{\mu\dagger}$$
$$+ \left(Y_{\bar{Q}L}\bar{Q}_{\rm L}\gamma_\mu L_{\rm L} + Y_{\bar{D}E}\bar{d}_{\rm R}\gamma_\mu e_{\rm R} \right) V_1^{\mu\dagger}$$

- Using the $\tilde{L}_\mu$-pattern, LQs S_3, V_3 and V_1 induce $C_9^{{\rm NP}\mu} = -C_{10}^{{\rm NP}\mu}$
- R_K can be explained, while experimental bounds from Kaon decays, $\mu - e$-conversion and B-mixing are satisfied
- In V_1 right-handed couplings can induce large effects in Kaon decays and $\mu \to e\gamma$ if FN-cancellations occur
  Solution: Flip signs of FN charges $q(E)$

Summary and conclusion

- Flavor symmetries that explain quark and lepton masses and mixings give rise to patterns for LQ couplings
- Generic suppression of lepton doublet couplings
$\Rightarrow$ Chirality-flipping contributions $>$ SM-like LL-operators
- Constraints from Kaon decays, $\mu - e$-conversion and $b \to s\nu\nu$ limit the reach of LQ effects in flavor observables
$\to$ present world average of $R_{D^{(*)}}$ cannot be explained
- Natural explanations of R_K are possible using muon isolation patterns
- Due to the suppression of the couplings, the LQ mass needs to be relatively small (several hundred GeV to a few TeV)
$\Rightarrow$ close to experimental bounds of direct searches at ATLAS and CMS