

Confronting QUARK-LEPTON UNIFICATION with LEPTON FLAVOUR UNIVERSALITY VIOLATION

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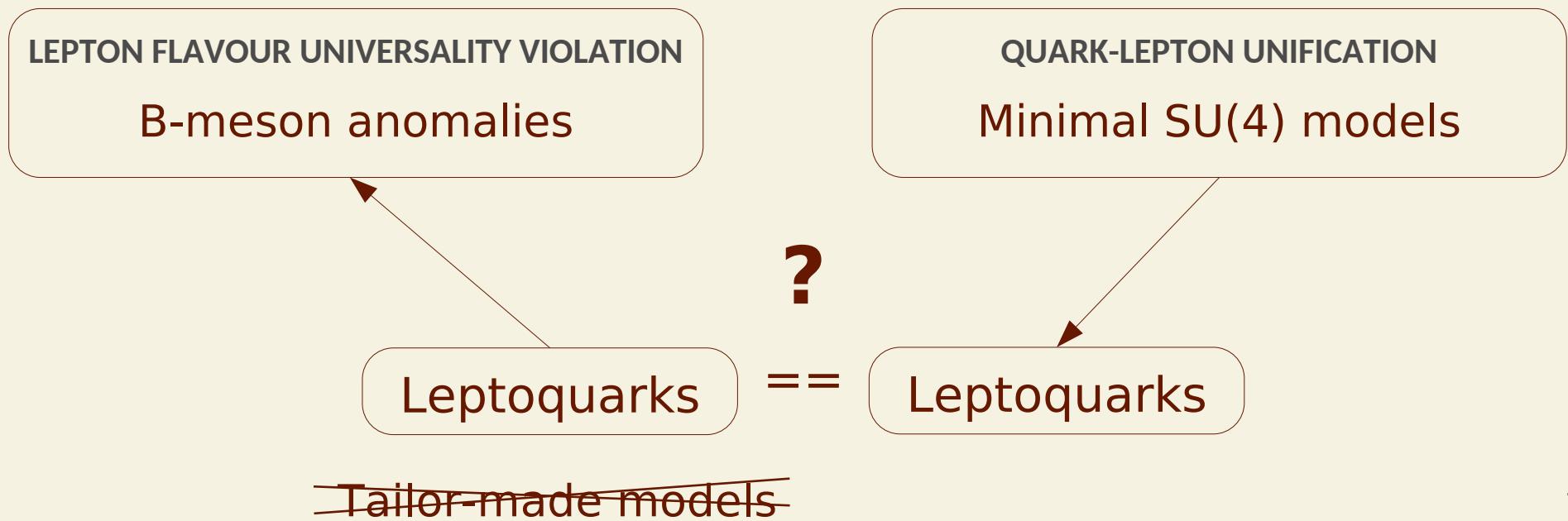
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Stavanger, Norway



Motivation

- Non-observation of New Physics:
 - exclusion of non-decoupling SM extensions
 - decoupling models: usually only bounds on parameter space
- Observation of New Physics:
 - exclusion of whole models (even decoupling ones)



Minimal SU(4) model(s)

A. D. Smirnov (et al.)

- The Minimal quark - lepton symmetry model and the limit on Z' mass
Phys. Lett. B346 (1995) 297-302 arXiv: hep-ph/9503239
- Phys. Lett. B431 (1998) 119-126 arXiv: hep-ph/9805339
- Mod. Phys. Lett. A20 (2005) 3003-3012 arXiv: 0511149
- Mod. Phys. Lett. A23 (2008) 2907-2913 arXiv: 0807.4486
- Mod. Phys. Lett. A24 (2009) 1199-1207 arXiv: 0902.2931
- Mod. Phys. Lett. A31 (2016) 39, 1650224 arXiv: 1610.08409
- Vector leptoquark mass limits and branching ratios of $K_L^0, B^0, B_s \rightarrow l_i^+ l_j^-$ decays with account of fermion mixing...
Mod. Phys. Lett. A33 (2018) 1850019 arXiv: 1801.02895

vanilla
version

P. Fileviez Pérez, M. B. Wise

- Low-scale quark-lepton unification
Phys. Rev. D88 (2013) 057703 arXiv: 1307.6213

inverse
seesaw

T. Faber, W. Porod, M. Hudec, M. Malinský, H. Kolešová, F. Staub, Y. Liu

- A unified LQ model confronted with lepton non-universality in B-meson decays
Phys. Lett. B 787 (2018) 159-166 arXiv: 1808.05511
- Collider phenomenology of a unified LQ model
Phys. Rev. D 101, 095024 (2020)

Minimal SU(4) model(s)

- $SU(4)_C \times SU(2)_L \times U(1)_R$

$$A_\mu^{\text{SU}(4)} = \begin{pmatrix} G_\mu + \frac{1}{\sqrt{12}} A_\mu^{15} & U_{1\mu} \\ U_{1\mu}^\dagger & \frac{-3}{\sqrt{12}} A_\mu^{15} \end{pmatrix}$$

Quark-Lepton unification

► natural LeptoQuark environment

- No extra charged fermions

mandatory: ν_R

optional: extra singlet \rightarrow inverse seesaw

- Minimal scalar sector

► Cascade SSB

► Independent fermion masses

► $\chi_{(4,1,+1/2)} = \begin{pmatrix} \bar{S}_1^{\dagger} (3,1,+2/3) \\ \chi_0^0 (1,1,0) \end{pmatrix}$

► $H_{(1,2,+1/2)}$

► $\Phi_{(15,2,+1/2)} = \begin{pmatrix} G_{(8,2,+1/2)} + \frac{H_2}{\sqrt{12}} & R_2 (3,2,+7/6) \\ \tilde{R}_2^\dagger (\bar{3},2,-1/6) & \frac{-3}{\sqrt{12}} H_2 (1,2,+1/2) \end{pmatrix}$

$$F_{(4,2,0)} = \binom{Q}{L}$$

$$f_{u(4,1,+1/2)}^c = (u_R^c \quad \nu_R^c)$$

$$f_{d(4,1,+1/2)}^c = (d_R^c \quad e_R^c)$$

$$N_{(1,1,0)}$$

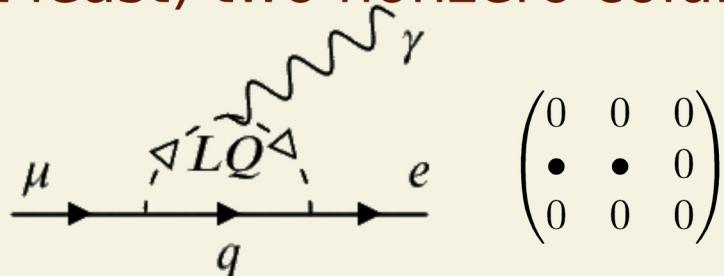
LF[U]V in LeptoQuark interactions

$$\mathcal{L}_{\text{LQ-int}} = (\bar{d} \quad \bar{s} \quad \bar{b}) \begin{pmatrix} y_{de} & y_{d\mu} & y_{d\tau} \\ y_{se} & y_{s\mu} & y_{s\tau} \\ y_{be} & y_{b\mu} & y_{b\tau} \end{pmatrix} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} LQ^{+2/3}$$

Lepton Flavor violation



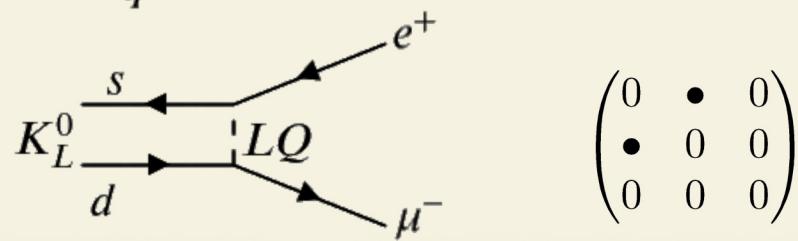
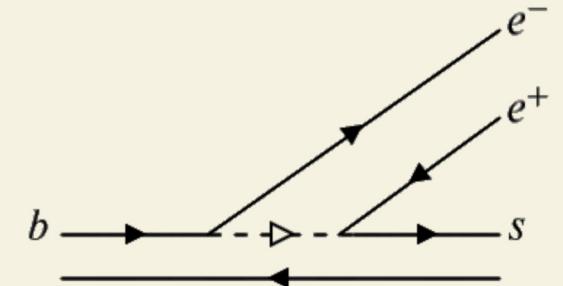
(At least) two nonzero columns



Lepton Flavor Universality violation



Two (or more) columns differ



$$\begin{pmatrix} 0 & \bullet & 0 \\ \bullet & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

LeptoQuarks in minimal $SU(4)$ model

- scalar $\tilde{R}_2 \sim (3, 2, +1/6)$
 - generally not useful for B-anomalies
- vector LQ $U_1 \sim (3, 1, +2/3)$
 - Unitary interaction matrices
- scalar $R_2 \sim (3, 2, +7/6)$

$$\begin{array}{ccc} e_L & \mu_L & \tau_L \\ d_L \begin{pmatrix} u_{de} & u_{d\mu} & u_{d\tau} \\ u_{se} & u_{s\mu} & u_{s\tau} \\ u_{be} & u_{b\mu} & u_{b\tau} \end{pmatrix} & & d_R \begin{pmatrix} v_{de} & v_{d\mu} & v_{d\tau} \\ v_{se} & v_{s\mu} & v_{s\tau} \\ v_{be} & v_{b\mu} & v_{b\tau} \end{pmatrix} \\ s_L & & s_R \\ b_L & & b_R \end{array}$$

- LFV constraints $m_{U_1} > 60 \text{ TeV}$
[1801.02895]

$$d_L \begin{pmatrix} e_R & \mu_R & \tau_R \\ u_{de}m_d - v_{de}m_e & u_{d\mu}m_d - v_{d\mu}m_\mu & u_{d\tau}m_d - v_{d\tau}m_\tau \\ u_{se}m_s - v_{se}m_e & u_{s\mu}m_s - v_{s\mu}m_\mu & u_{s\tau}m_s - v_{s\tau}m_\tau \\ u_{be}m_b - v_{be}m_e & u_{b\mu}m_b - v_{b\mu}m_\mu & u_{b\tau}m_b - v_{b\tau}m_\tau \end{pmatrix} \frac{\sqrt{3/2}}{v_{ew} \cos \beta}$$

- used for R(D) ... does not work here
- in general can explain R(K) via NP in electrons

$$R_{K^{(*)}} = \frac{\text{BR}(B \rightarrow K^{(*)}\mu^+\mu^-)}{\text{BR}(B \rightarrow K^{(*)}e^+e^-)} \leq 1$$

Scalar potential

$$\begin{aligned}
V = & \mu_H^2 |H|^2 + \mu_\chi^2 |\chi|^2 + \mu_\Phi^2 \text{Tr}(|\Phi|^2) + \lambda_1 |H|^2 |\chi|^2 + \lambda_2 |H|^2 \text{Tr}(|\Phi|^2) + \lambda_3 |\chi|^2 \text{Tr}(|\Phi|^2) \\
& + (\lambda_4 H_i^\dagger \chi^\dagger \Phi^i \chi + \text{h.c.}) + \lambda_5 H_i^\dagger \text{Tr}(\Phi_j^\dagger \Phi^i) H^j + \lambda_6 \chi^\dagger \Phi^i \Phi_i^\dagger \chi + \lambda_7 |H|^4 + \lambda_8 |\chi|^4 + \lambda_9 \text{Tr}(|\Phi|^4) \\
& + \lambda_{10} (\text{Tr}|\Phi|^2)^2 + \left(\lambda_{11} H_i^\dagger \text{Tr}(\Phi^i \Phi^j) H_j^\dagger + \lambda_{12} H_i^\dagger \text{Tr}(\Phi^i \Phi^j \Phi_j^\dagger) + \lambda_{13} H_i^\dagger \text{Tr}(\Phi^i \Phi_j^\dagger \Phi^j) + \text{h.c.} \right) \\
& + \lambda_{14} \chi^\dagger |\Phi|^2 \chi + \lambda_{15} \text{Tr}(\Phi_i^\dagger \Phi^j \Phi_j^\dagger \Phi^i) + \lambda_{16} \text{Tr}(\Phi_i^\dagger \Phi^j) \text{Tr}(\Phi_j^\dagger \Phi^i) + \lambda_{17} \text{Tr}(\Phi_i^\dagger \Phi_j^\dagger) \text{Tr}(\Phi^i \Phi^j) \\
& + \lambda_{18} \text{Tr}(\Phi_i^\dagger \Phi_j^\dagger \Phi^i \Phi^j) + \lambda_{19} \text{Tr}(\Phi_i^\dagger \Phi_j^\dagger \Phi^j \Phi^i)
\end{aligned}$$



$$m_G^2 = \left(\frac{\sqrt{3}\lambda_4}{4} \tan \beta - \frac{3}{8} (\lambda_6 + \lambda_{14}) \right) v_\chi^2,$$

$$m_{R_2}^2 = \left(\frac{\sqrt{3}\lambda_4}{4} \tan \beta + \frac{\lambda_{14} - 3\lambda_6}{8} \right) v_\chi^2,$$

$$m_{\tilde{R}_2}^2 = \left(\frac{\sqrt{3}\lambda_4}{4} \tan \beta + \frac{\lambda_6 - 3\lambda_{14}}{8} \right) v_\chi^2,$$

$$m_{\hat{H}}^2 = \frac{\sqrt{3}\lambda_4}{2 \sin(2\beta)} v_\chi^2,$$



$$m_G^2 + 2m_{\hat{H}}^2 \sin^2 \beta = \frac{3}{2} (m_{R_2}^2 + m_{\tilde{R}_2}^2)$$

... the only constraint
on scalar masses

Scalar LQ R_2 in the minimal SU(4)

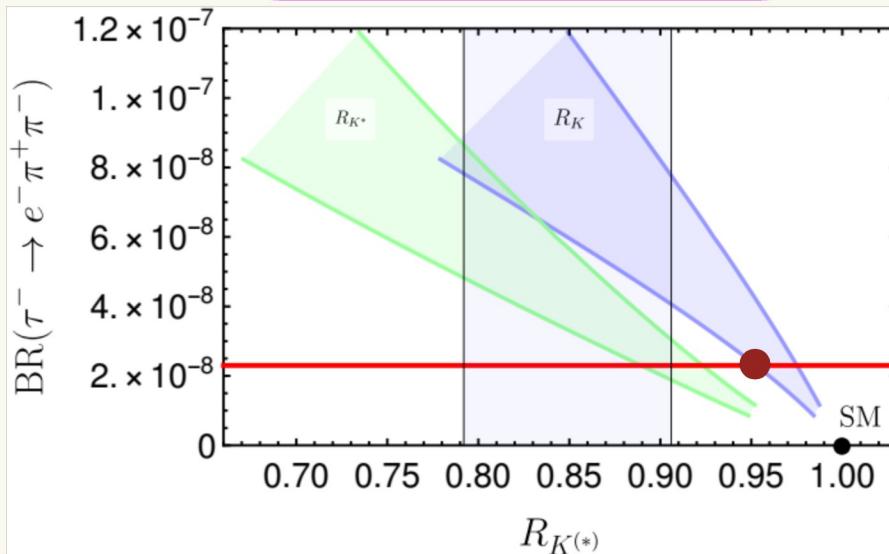
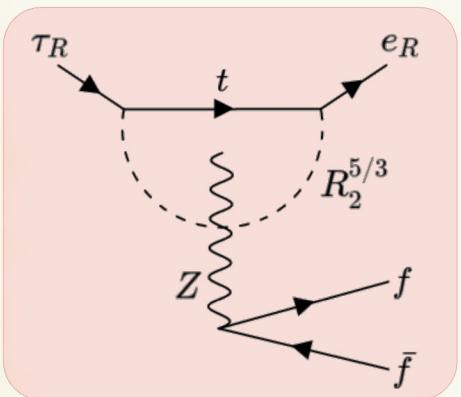
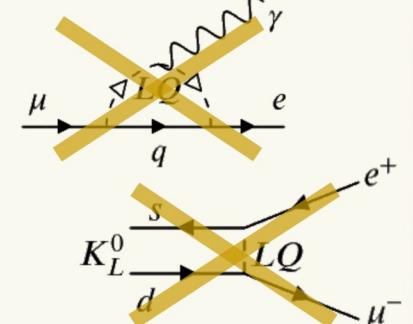
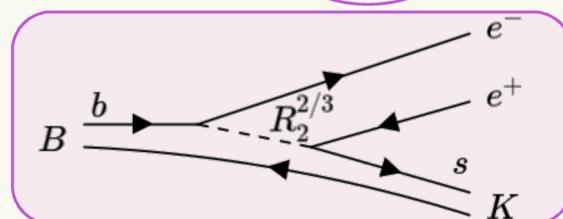
$$R_2 = \begin{bmatrix} R^{5/3} \\ R^{2/3} \end{bmatrix} \sim (3, 2, +\frac{7}{6})$$

$C_9 = +C_{10}$

$$\begin{array}{c} e_R \quad \mu_R \quad \tau_R \\ d_L \begin{pmatrix} u_{de}m_d - v_{de}m_e & u_{d\mu}m_d - v_{d\mu}m_\mu & u_{d\tau}m_d - v_{d\tau}m_\tau \\ u_{se}m_s - v_{se}m_e & u_{s\mu}m_s - v_{s\mu}m_\mu & u_{s\tau}m_s - v_{s\tau}m_\tau \\ u_{be}m_b - v_{be}m_e & u_{b\mu}m_b - v_{b\mu}m_\mu & u_{b\tau}m_b - v_{b\tau}m_\tau \end{pmatrix} \frac{\sqrt{3/2}}{v_{ew} \cos \beta} \\ s_L \\ b_L \end{array}$$

Best one can do:

$$\hat{Y}_4 = \sqrt{\frac{3}{2}} \frac{1}{v_{ew} \cos \beta} \begin{pmatrix} 0 & 0 & m_\tau \sin \phi \\ m_s/\sqrt{2} & 0 & m_\tau \cos \phi \\ m_b/\sqrt{2} & 0 & -m_b/\sqrt{2} \end{pmatrix}$$



T. Faber et al.

*Collider phenomenology
of a unified leptoquark
model*

Phys. Rev. D **101**, 095024
(2020)

Conclusions of 1st part

- Minimal quark-lepton unification is incompatible with the current values of any of the B-meson anomalies.
- The excess in $R(K^{(*)})$ can be accommodated partially.
 - predictions for Belle-II $\tau \rightarrow e\gamma, \quad \tau \rightarrow e\pi$
 - predictions for LHC
$$\text{BR}(R_2^{+2/3} \rightarrow e^+ j_b) \simeq \text{BR}(R_2^{+2/3} \rightarrow \tau^+ j_b) \simeq \frac{m_b^2}{2m_\tau^2} \text{BR}(R_2^{+2/3} \rightarrow \tau^+ j)$$
$$\text{BR}(R_2^{+5/3} \rightarrow e^+ t) \simeq \text{BR}(R_2^{+5/3} \rightarrow \tau^+ t) \simeq \frac{m_b^2}{2m_\tau^2} \text{BR}(R_2^{+5/3} \rightarrow \tau^+ j)$$
 - and much more in *Phys. Rev. D 101, 095024 (2020)*

2nd part: gauge LQ resurrection

WORK IN PROGRESS

- Stay within $SU(4) \times SU(2) \times U(1)$, add extra vector-like leptons

$$n_{L'} = 1$$

$$\begin{array}{c} e_L \quad \mu_L \quad \tau_L \\ \hline u_{de} \quad u_{d\mu} \quad u_{d\tau} \quad u_{d4} \\ u_{se} \quad u_{s\mu} \quad u_{s\tau} \quad u_{s4} \\ u_{be} \quad u_{b\mu} \quad u_{b\tau} \quad u_{b4} \\ u_{4e} \quad u_{4\mu} \quad u_{4\tau} \quad u_{44} \end{array}$$

$$n_{e'} = 2$$

$$\begin{array}{c} e_R \quad \mu_R \quad \tau_R \\ \hline v_{de} \quad v_{d\mu} \quad v_{d\tau} \quad v_{d4} \quad v_{d5} \\ v_{se} \quad v_{s\mu} \quad v_{s\tau} \quad v_{s4} \quad v_{s5} \\ v_{be} \quad v_{b\mu} \quad v_{b\tau} \quad v_{b4} \quad v_{b5} \\ v_{4e} \quad v_{4\mu} \quad v_{4\tau} \quad v_{44} \quad v_{45} \\ v_{5e} \quad v_{5\mu} \quad v_{5\tau} \quad v_{54} \quad v_{55} \end{array}$$

For combinations of $n_{L',e'} = 0, 1, \dots$ list **all first signals** predicted by any shape of the LQ mixing matrix.

Find smallest ($n_{L'}$, $n_{e'}$) needed to reproduce some of the current B-meson anomalies

- How to:

combine analytical approach with numerical scanning
flavio, smelli...

Thank you for your attention

Matěj Hudec