NATURAL LFU VIOLATION

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Mariano Quirós

IFAE/ICTP-SAIFR

Outline

- Introduction
- The model
- Explaining the B-anomalies
- Experimental constraints
- Concluding remarks

Based on:
E. Megias, G. Panico, O. Pujolas, MQ, 1608.02362
E. Megias, MQ, L. Salas, 1703.06019; 1707.08014

See also: "Instant workshop in B-meson anomalies" (CERN, 17-19 May 2017) and 2018 Zurich Phenomenology Workshop "Flavours: light, heavy and dark" (Zurich, 15-17 Jan 2018)

Introduction

- The LHCb Collaboration has determined the ratios for $\bar{B} \to \bar{K}\ell\ell$ ($\ell = \mu, e$) for muons over electrons for $1 < q^2/GeV^2 < 6$ (central bin) yielding

$$R_K = \frac{\mathcal{B}(\bar{B} \to \bar{K}\mu\mu)}{\mathcal{B}(\bar{B} \to \bar{K}ee)} = 0.745^{+0.090}_{-0.074} \pm 0.032$$

- As the SM result is

$$R_K^{\rm SM} \simeq 1$$

this result departs from the SM prediction by ~ 2.6

- This suggests a Lepton Flavor Universality (LFU) Violation in the process

$$b \to s\ell\ell$$

- Very recently the same tendency has been confirmed for the ratio

$$R_{K^*} = \frac{\mathcal{B}(\bar{B} \to \bar{K}^* \mu\mu)}{\mathcal{B}(\bar{B} \to \bar{K}^* ee)} = \begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.024, & 0.045 < q^2/GeV^2 < 1.1 \\ 0.685^{+0.113}_{-0.069} \pm 0.047, & 1.1 < q^2/GeV^2 < 6 \end{cases}$$

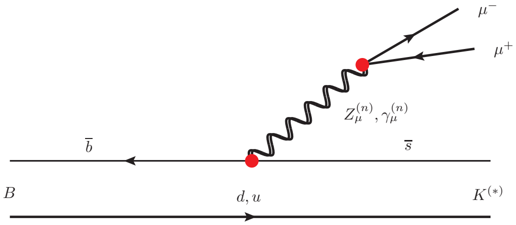
which departs from the SM prediction $\sim 2.5\sigma$ and also suggests LFU Violation in the process

$$b \to s\ell\ell$$

- As in the Standard Model $R_{K^{(*)}} \simeq 1$ (central bin), this would imply

NEW PHYSICS COUPLED TO b AND/OR μ (NOT e) SECTOR

- A solution to this problem can be provided by vector bosons which couple strongly to bottoms and/or muons but not to electrons
- A typical new physics diagram



gives rise to effective operators

$$\mathcal{O}_9^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)\,, \qquad \mathcal{O}_{10}^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,,$$
$$\mathcal{O}_9^{\prime\ell} = (\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma^\mu\ell)\,, \qquad \mathcal{O}_{10}^{\prime\ell} = (\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,.$$

- The charged current decays $\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau$ have been measured by the BaBar, Belle and LHCb collaborations which provide

$$R_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^- \bar{\nu}_\ell)}, \quad (\ell = \mu \text{ or } e)$$

- The averaged experimental results

$$R_D = 0.403 \pm 0.047, \quad R_{D^*} = 0.310 \pm 0.017$$

again depart from the Standard Model predictions

$$R_D = 0.300 \pm 0.011, \quad R_{D^*} = 0.254 \pm 0.004$$

by 2.2σ and 3.3σ, although the combined deviation is $\sim 4\sigma$

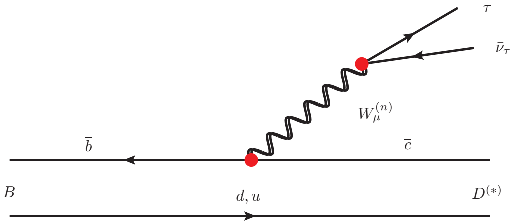
- This suggests Lepton Flavor Universality (LFU) Violation in the process

$$b \to c\tau\nu_\tau$$

- This would lead to

NEW PHYSICS MAINLY COUPLED TO THE b AND τ SECTORS

- A solution to this problem can be given by charged vector bosons which couple to taus much more strongly than to muons and electrons
- A new physics diagram



gives rise to the effective operator

$$\mathcal{O}^\ell = (\bar{c}\gamma^\nu P_L b)(\bar{\ell}\gamma_\nu \nu_\ell), \ (\ell = \tau)$$

The model (solving the naturalness problem)

- I will present a warped model where those ideas can be realized
- A 5D model with two branes at $y = 0$ (UV) and $y = y_1$ (IR), and metric $A(y)$

$$ds^2 = e^{-2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2, \quad A(y_1) \simeq 35 \text{ (hierarchy problem)}$$

- We are using a soft-wall (SW) metric with a singularity beyond the IR

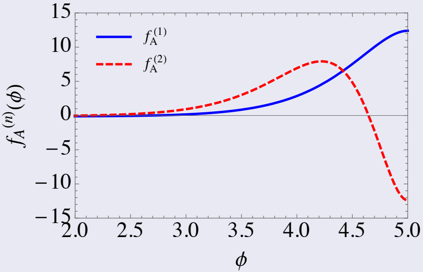
$$\lim_{y\to y_s} A(y) = \infty, \quad y_s > y_1$$

- This can be easily achieved by a stabilizing bulk field ϕ with an exponential (super)potential, as e.g.

$$W(\phi) = 6k\left(1 + e^{a\phi}\right)^b \quad \text{e.g. } b = 2, a = 0.15 \text{ (RS is } b = 0)$$

- All SM fields propagate in the bulk: gauge vectors, Higgs, fermions
- Every field has the lowest mode and the Kaluza-Klein (KK) excitations
- The Higgs zero mode is localized towards the IR to solve the hierarchy problem
- All KK excitations are localized towards the IR brane

For instance, $n = 1, 2$ KK modes of gauge bosons:



- KK modes of gauge bosons interact strongly (weakly) with IR (UV) localized fields

- The SM fermion $f_{L,R}$ is the zero mode of the 5D fermion $\Psi(y,x)$ with appropriate boundary conditions and a Dirac mass term

$$\mathcal{L}_5 = M_{f_{L,R}}(y)\bar{\Psi}\Psi, \quad M_{f_{L,R}}(y) = \mp c_{f_{L,R}} W(\phi)$$

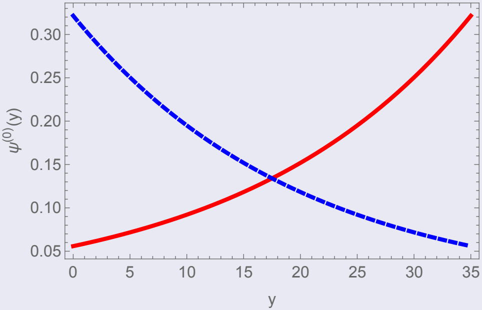
- Explicitely the zero mode (in flat coordinates) is given by

$$\psi^{(0)}_{L,R}(y,x) = \frac{e^{(1/2-c_{L,R})A(y)}}{\left(\int dy\, e^{A(1-2c_{L,R})}\right)^{1/2}} f_{L,R}(x)$$

where $f_{L,R}(x)$ are SM fermions

- Fermions with $c < 0.5$ ($c > 0.5$) are localized towards the IR (UV) brane.

- For example the profile of fermions with $c = 0.45$ (solid red) and $c = 0.55$ (dashed blue) are

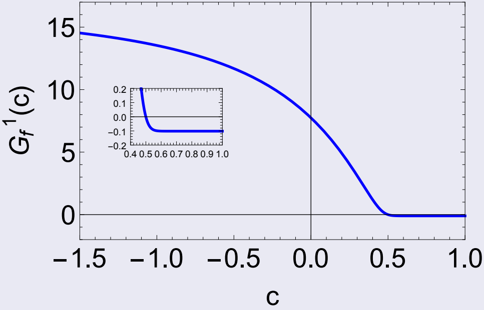


- Fermions with $c < 0.5$ ($c > 0.5$) are interpreted as partly composite (elementary) in the dual holographic theory

The coupling with fermions is

$$G_f^n(c_{L,R})\, g^{SM}_{f_{L,R}}\, A_\mu^n \bar{f}_{L,R}\gamma^\mu f_{L,R}$$

- The interaction of gauge KK modes with leptons is Lepton Flavor Non-Universal, depending on the values of $c_{\ell_{L,R}}$ ($\ell = \tau, \mu, e$)



- The coupling with IR localized (composite) fermions is stronger than the coupling with UV localized (elementary) fermions

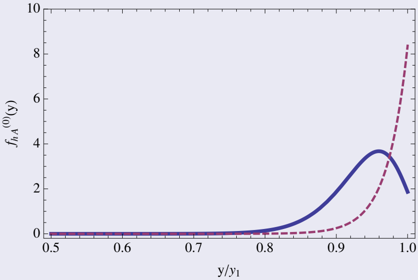
- We can understand the improvement from electroweak constraints in the SW model by the different behaviour of the Higgs profile at the IR brane location y_1
- In fact the normalized physical Higgs wave function is defined as

$$f_{hA}^{(0)}(y) = N_0 e^{-A(y)} h(y)$$

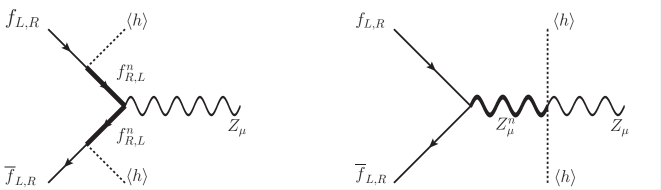
$$h(y) = e^{bky}, \;\; b \geq 2$$

- As KK-modes are localized towards the IR brane their contribution to the electroweak observables T and S is smaller than in RS

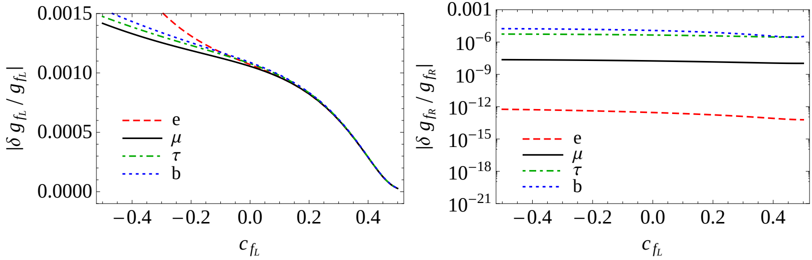
Solid=SW, dashed=RS



The most constraining observable is the $Z\bar{f}f$ coupling from the diagrams

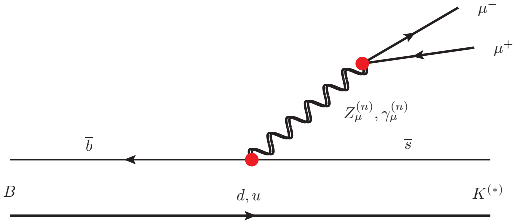


yielding



The B-anomalies

- The SM departure for $R_{K^{(*)}}$ is generated by the diagram



- The FCNC current $(\bar{b}\gamma^\mu s)$ is generated from

$$\left(V_d^\dagger G_d^n V_d\right)_{32}$$

$$G_d^n = \mathrm{diag}(G_d^n(c_d), G_s^n(c_s), G_b^n(c_b)) \neq G^n(c)\mathbf{1}_3$$

- Where $V_{d_{L,R}}$ is the unitary matrix diagonalizing the *down* mass matrix

- In the absence of a general (UV) theory providing the 5D Yukawa couplings, we will just consider the general form for these matrices by assuming that they reproduce the physical CKM matrix V, i.e. they satisfy the condition $V \equiv V_{u_L}^\dagger V_{d_L}$
- Given the hierarchical structure of the quark mass spectrum and mixing angles, we can then assume for the matrices V, V_{d_L} and V_{u_L} Wolfenstein-like parametrization

$$V_{d_L} = \begin{pmatrix} 1-\frac{1}{2}\lambda_0^2 & \lambda_0 & (V_{d_L})_{13} \\ -\lambda_0 & 1-\frac{1}{2}\lambda_0^2 & -A\lambda^2(r-1) \\ (V_{d_L})_{31} & A\lambda^2(r-1) & 1 \end{pmatrix}$$

$$(V_{d_L})_{13} = -A\lambda^2\lambda_0(r-1)(\rho_0 - i\eta_0)$$

and

$$(V_{d_L})_{31} = -A\lambda^2\lambda_0(r-1)(1-\rho_0 - i\eta_0)$$

- They give rise to the Wilson coefficients

$$\Delta C_9^{(\prime)\ell} = (r-1)\sum_{X=Z,\gamma}\sum_n \frac{2\pi g^2 g_{\ell_V}^{X_n}\left(g_{b_{L(R)}}^{X_n} - g_{s_{L(R)}}^{X_n}\right)}{\sqrt{2}G_F\alpha c_W^2 M_n^2}$$

$$\Delta C_{10}^{(\prime)\ell} = -(r-1)\sum_{X=Z,\gamma}\sum_n \frac{2\pi g^2 g_{\ell_A}^{X_n}\left(g_{b_{L(R)}}^{X_n} - g_{s_{L(R)}}^{X_n}\right)}{\sqrt{2}G_F\alpha c_W^2 M_n^2}$$

where

$$g_{f_{L,R}}^{X_n} = g_{f_{L,R}}^{X} G_{f_{L,R}}^{n}, \quad X = Z,\gamma$$

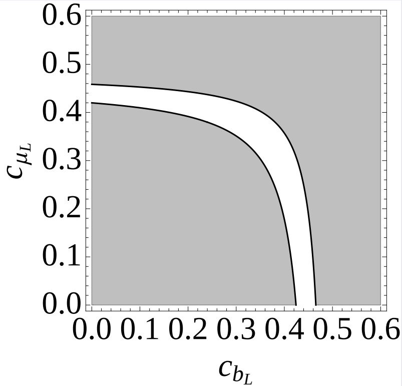
$$g_f^Z = T_{3f} - Q_f s_W^2, \quad g_f^\gamma = Q_f s_W c_W$$

- Different qualitative behaviors for [$M_{KK} = 2$ TeV]

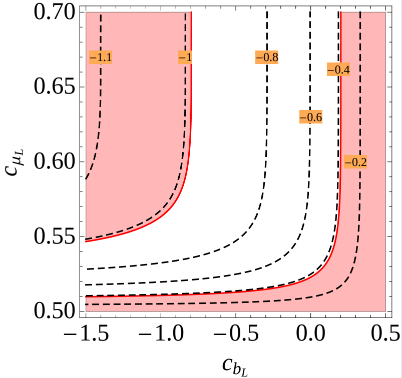
$$r < 1 \ \& \ r > 1$$

- The region allowed by $b \to s\ell\ell$ data (fit of ΔC_9^μ) is

$r < 1$: $r = 0.75$, $c_{e_L} = 0.5$



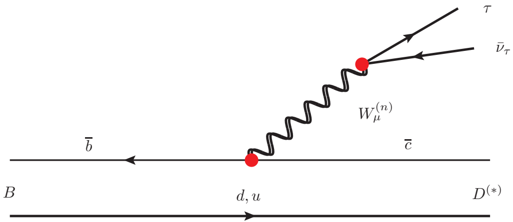
$r > 1$: $r = 2.3$, $c_{e_L} = 0.5$



- So

b_L is composite and μ_L is composite (elementary) for $r < 1$ ($r > 1$)

- The SM departure for $R_{D^{(*)}}$ is generated by the diagram



- The FC charged current $(\bar{b}_L \gamma^\mu c_L)$ is generated from

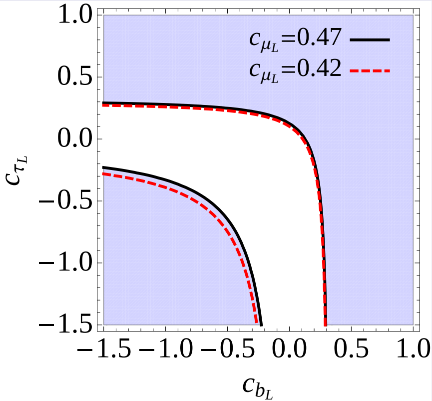
$$\left(V_{d_L}^\dagger G_{d_L}^n V_{u_L} \right)_{32}$$

$$G_{d_L}^n = \mathrm{diag}(G_{d_L}^n(c_{d_L}), G_{s_L}^n(c_{s_L}), G_{b_L}^n(c_{b_L})), \quad c_{u_L} = c_{d_L}$$

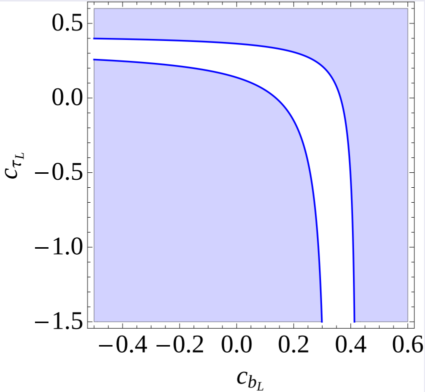
- Where $V_{u_{L,R}}$ is the unitary matrix diagonalizing the *up* mass matrix
- We have considered a parametrization such that $V_{d_L}^\dagger V_{u_L} = V_{CKM}$

- The relevant parameters here are c_{b_L}, c_{τ_L}
- The region allowed by $R_{D^{(*)}}$ data is the white region

$r = 0.75$



$r = 2.3$



For $r < 1$ τ_L and b_L are more composite than for $r > 1$

Constraints

The main constraints are those from

- The experimental value of the coupling $g^Z_{\tau_L}$ [a]

[a] S. Schael et al. (SLD Electroweak Group, DELPHI, ALEPH, SLD, SLD Heavy Flavour Group, OPAL, LEP Electroweak Working Group, L3), Phys. Rept. 427, 257 (2006)

- LFU tests, as e.g. $\tau \to \mu\nu\bar{\nu}$ Vs $\mu \to e\nu\bar{\nu}$ [a]

[a] F. Feruglio, P. Paradisi, and A. Pattori, Phys. Rev. Lett. 118, 011801 (2017); F. Feruglio, P. Paradisi, and A. Pattori (2017), 1705.00929; A. Pich, Prog. Part. Nucl. Phys. 75, 41 (2014)

- Constraints from flavor physics [a]

[a] G. Isidori, Flavour Physics and Implication for New Phenomena, Adv. Ser. Direct. High Energy Phys. 26 (2016) 339-355, [1507.00867]

The coupling $g^Z_{\tau_L}$

- We also obtain the effective Lagrangian

$$\mathcal{L}_{eff} = \frac{C_n^{t\ell}}{M_n^2}(\bar{t}_L\gamma_\mu t)(\ell_L\gamma^\mu\ell_L)$$

$$C_n^{t\ell} = -\frac{g^2}{c_W^2}\left(g^{Z_n}_{u_L}g^{Z_n}_{\ell_L} + g^{\gamma_n}_{u_L}g^{\gamma_n}_{\ell_L}\right)$$

- $g^Z_{\tau_L}$ receives leading loop corrections proportional to h_t^2

$$\Delta g^Z_{\ell_L} \simeq \frac{v^2}{M_n^2}\frac{1}{16\pi^2}\left(3h_t^2 C_n^{t\ell}\log\frac{M_n}{m_t} + \mathcal{O}(g^4)\right)$$

- Experimentally

$$g^Z_{\tau_L} = -0.26930 \pm 0.00058$$

LFU tests

- The value of $R_{D^{(*)}}$ also has to agree with flavor universality tests in tau decays. In particular the observables

$$R_\tau^{\tau/\ell} = \frac{\mathcal{B}(\tau \to \ell\nu\bar{\nu})/\mathcal{B}(\tau \to \ell\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(\mu \to e\nu\bar{\nu})/\mathcal{B}(\mu \to e\nu\bar{\nu})_{\rm SM}}, \quad (\ell = \mu, e)$$

- Subject to the 95% CL experimental bounds

$$R_\tau^{\tau/\mu} \in [0.996, 1.008], \quad R_\tau^{\tau/e} \in [1.000, 1.012]$$

- In our model, fixing $c_{e_L} = 0.5$ implies that $R_\tau^{\tau/e} = 1$
- Including one-loop radiative corrections

$$R_\tau^{\tau/\mu} = 1 + 2\frac{m_W^2}{M_n^2} G^n_{\tau_L}(G^n_{\mu_L} - 0.065 G^n_{b_L})$$

Flavor observables

- New physics contributions to $\Delta F = 2$ processes come from the exchange of gluon KK modes in flavor observables
- Integrating out the massive KK gluons gives rise to

$q = d, u$

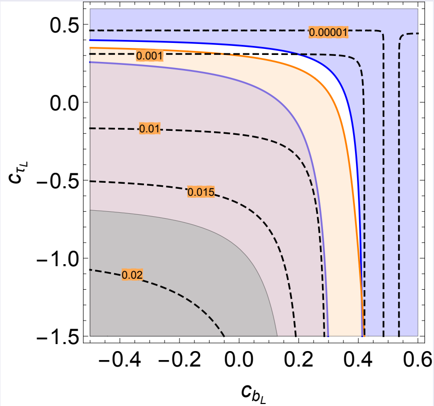
$$\mathcal{L}_{\Delta F=2} = \frac{c_{qij}^{LL(n)}}{M_n^2}(\overline{q}_{iL}\gamma^\mu q_{jL})(\overline{q}_{iL}\gamma_\mu q_{jL}) + \frac{c_{qij}^{RR(n)}}{M_n^2}(\overline{q}_{iR}\gamma^\mu q_{jR})(\overline{q}_{iR}\gamma_\mu q_{jR}) + \frac{c_{qij}^{LR(n)}}{M_n^2}(\overline{q}_{iR} q_{jL})(\overline{q}_{iL} q_{jR})$$

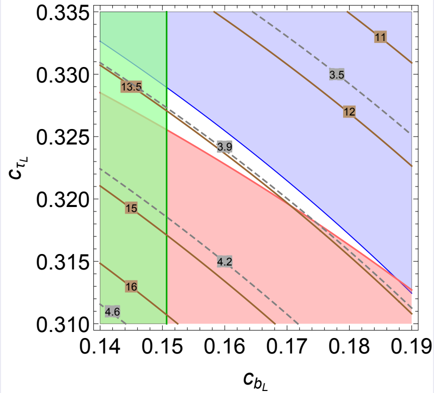
$$c_{dij}^{LL,RR(n)} = \frac{g_s^2}{6}\left[(V_{d_L}^*)_{3i}(V_{d_L})_{3j}\right]^2 \left(G_{b_{L,R}}^n - G_{q_{L,R}}^n\right)^2 ,$$

$$c_{dij}^{LR(n)} = g_s^2 (V_{d_L}^*)_{3i}(V_{d_L})_{3j}(V_{d_R}^*)_{3i}(V_{d_R})_{3j}\left(G_{b_L}^n - G_{q_L}^n\right)\left(G_{b_R}^n - G_{q_R}^n\right)$$

- Main constraints from Δm_K and ϵ_K

- The constraints considerably reduce the available space left by experimental data: case $r > 1$ favored (for $r = 2.3$)





Left panel: Blue: $R_{D^{(*)}}$; Orange: g_τ^Z; Brown: $bb \to Z^{(n)}/\gamma^{(n)} \to \tau\tau$

Right panel: Red: $R_\tau^{\tau/\mu}$; Green: flavor

Concluding remarks

- To prevent strong bounds from

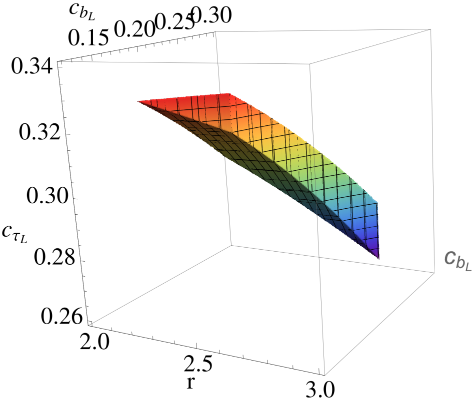
$$\mu \to e\gamma,\ \tau \to \mu\gamma, \ldots$$

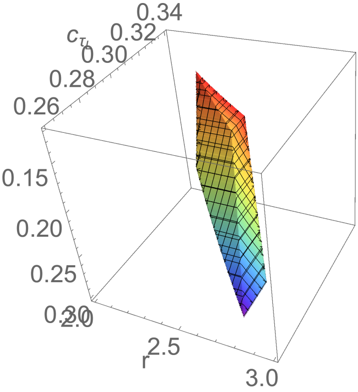
  we have assumed no Lepton Flavor Violation (LFV)
- We are assuming that the 5D Yukawa couplings are such that the charged leptons are diagonal in the weak basis, so that $V_{\ell_{L,R}} \simeq 1$
- The required alignment in the lepton sector depends on the UV completion of the theory.
- This can be obtained by imposing a

$$U(1)^3$$

  flavor symmetry in the lepton sector broken only by the tiny effects due to the neutrino masses

The available 3D volume in the space (r, c_{b_L}, c_{τ_L})





The range of possible values of r consistent with all experimental data

$$2.2 < r < 2.8$$

- We find agreement with $R_{K^{(*)}}$ and $R_{D^{(*)}}$ data at 95% CL, provided the third generation of left-handed fermions is composite, as

$$0.14 < c_{b_L} < 0.28, \quad \& \quad 0.265 < c_{\tau_L} < 0.33$$

- First and second generations of quarks and leptons are elementary
- We obtain the absolute limits from experimental constraints

$$R_{K^{(*)}} > 0.79 \quad \& \quad R_{D^{(*)}}/R_{D^{(*)}}^{\mathrm{SM}} < 1.13$$

as compared with the experimental data (at 1σ)

$$0.664 < R_K < 0.841, \quad 0.601 < R_{K^*} < 0.807$$

$$1.20 < R_D/R_D^{\mathrm{SM}} < 1.54, \quad 1.20 < R_{D^*}/R_{D^*}^{\mathrm{SM}} < 1.36$$

- Finally our model predicts, for any value of the parameters the absolute range at 95% CL for the branching ratio $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$

$$1.14 \times 10^{-5} \lesssim \mathcal{B}(B \to K\nu\bar{\nu}) \lesssim 2.55 \times 10^{-5}$$
$$2.70 \times 10^{-5} \lesssim \mathcal{B}(B \to K^{*}\nu\bar{\nu}) \lesssim 5.79 \times 10^{-5}$$

much larger than the SM prediction

$$\mathcal{B}(B \to K\nu\bar{\nu})_{\rm SM} = (3.98 \pm 0.47) \times 10^{-6}$$

as compared with experimental bounds (at 90% CL) from Belle

$$\mathcal{B}(B \to K\nu\bar{\nu}) < 1.6 \times 10^{-5}$$
$$\mathcal{B}(B \to K^{*}\nu\bar{\nu}) < 2.7 \times 10^{-5}$$

- Therefore...

... on the verge of experimental discovery/exclusion!!

- A similar analysis can be done with the branching ratio $\mathcal{B}(B \to K\tau\tau)$, as measured by the BaBar Collaboration providing the 90% CL bound,

$$\mathcal{B}(B \to K\tau\tau) < 2.25 \times 10^{-3}$$

much larger than the SM prediction

$$\mathcal{B}(B \to K\tau\tau)_{\rm SM} = (1.44 \pm 0.15) \times 10^{-7}$$

- The model predicts, for any value of the parameters the absolute range at 95% CL

$$1.9 \times 10^{-6} \lesssim \mathcal{B}(B \to K\tau\tau) \lesssim 2.0 \times 10^{-6}$$

much larger than the SM prediction but still far from experimental bounds!