Can one make sense of the collection of B-decay anomalies?

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with Isidori, Pattori, Senia

(and an extensive literature on leptoquarks)

B-physics "anomalies"

1. $b \longrightarrow c\tau\nu$

$$R_{D^*}^{\tau/\ell} = \frac{\mathcal{B}(B \to D^* \tau \nu)_{\rm exp}/\mathcal{B}(B \to D^* \tau \nu)_{\rm SM}}{\mathcal{B}(B \to D^* \ell \nu)_{\rm exp}/\mathcal{B}(B \to D^* \ell \nu)_{\rm SM}} = 1.28 \pm 0.08$$

$$R_{D}^{\tau/\ell} = \frac{\mathcal{B}(B \to D \tau \nu)_{\rm exp}/\mathcal{B}(B \to D \tau \nu)_{\rm SM}}{\mathcal{B}(B \to D \ell \nu)_{\rm exp}/\mathcal{B}(B \to D \ell \nu)_{\rm SM}} = 1.37 \pm 0.18 \,,$$

2. $b \longrightarrow s l^+ l^-$

$$R_K^{\mu/e} = \left.\frac{\mathcal{B}(B \to K \mu^+ \mu^-)_{\rm exp}}{\mathcal{B}(B \to K e^+ e^-)_{\rm exp}}\right|_{q^2 \in [1,6]{\rm GeV}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

(could be related to the P_5' anomaly in the q^2 distribution)

Both a $20 \div 30\%$ deviation from the SM

However tree (1) versus loop level (2)!

Question

Is there a flavour group $\mathcal{G}_F$ and a tree level exchange Φ such that:

1. With unbroken $\mathcal{G}_F$, Φ couples to the third generation of quarks and leptons only;

2. After small $\mathcal{G}_F$ breaking, the needed operators are generated

$$(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L)$$

$(\bar{b}_L \gamma_\mu s_L)(\bar{\mu} \gamma_\mu \mu)$ at suppressed level

Answer

$\mathcal{G}_F = \mathcal{G}_F^q \times \mathcal{G}_F^l$ "minimally" broken

$$\mathcal{G}_F^q = U(2)_Q \times U(2)_u \times U(2)_d \times U(1)_{d3}$$

$$\mathcal{G}_F^l = U(2)_L \times U(2)_e \times U(1)_{e3}$$

with mediators:

1. $V_\mu = (3,1)_{2/3}$ Lorentz vector, $\mathcal{G}_F$ singlet
2. $\mathbf{V}_\mu = (3,3)_{2/3}$ Lorentz vector, $\mathcal{G}_F$ singlet
3. $\Phi = (3,3)_{-1/3}$ Lorentz scalar, $\mathcal{G}_F$ singlet

(unique, if I were a mathematician)

Weak MFV

$$U(2)_Q \times U(2)_u \times U(2)_d \times U(1)_{d3}$$

$$y_b = (1,1,1)_{-1} \quad \lambda_u = (2,\bar{2},1)_0 \quad \lambda_d = (2,1,\bar{2})_0 \quad \mathbf{V}_Q = (2,1,1)_0$$

1. gives a symmetry status to heavy and weakly mixed top
2. allows observables deviations from the SM by nearby BSM

$$\Rightarrow \quad Y_u = \left(\begin{array}{c|c} \lambda_u & y_t x_t \mathbf{V} \\ \hline 0 & y_t \end{array}\right) \qquad Y_d = \left(\begin{array}{c|c} \lambda_d & y_b x_b \mathbf{V} \\ \hline 0 & y_b \end{array}\right) \qquad \mathbf{V} = \begin{pmatrix} 0 \\ \epsilon \end{pmatrix}$$

mimicked in the lepton sector by: $U(2)_L \times U(2)_e \times U(1)_{e3}$

$$y_\tau = (1,1)_{-1} \quad \lambda_e = (2,\bar{2})_0 \quad \mathbf{V_L} = (2,1)_0$$

(except for neutrinos, due to $N_R^T M N_R$)

B, Isidori, Jones-Perez, Lodone, Straub
B, Buttazzo, Sala, Straub

Parameters after $\mathcal{G}_F$ breaking

e.g. in the vector-singlet case (but all similar)

$$\mathcal{L}_1 = g_U U_\mu(\bar{Q}_i \gamma_\mu F_{ij} L_j)$$

$$F_{ij} = \delta_{i3}\delta_{j3} + a V_{Qi}\delta_{j3} + b\delta_{i3} V^*_{Lj} + c V_{Qi} V^*_{Lj}$$

$$V_{Q,Li} = \delta_{i2}\epsilon_{Q,L}$$

$$M_{23}^{U,D,L} = \epsilon_Q,\ d\epsilon_Q, \epsilon_L \qquad V_{cb} = -V_{ts} = \epsilon_Q(d-1)$$

$\Rightarrow$ parameters:

$$\frac{g_U}{M_U^2},\ \epsilon_L$$

$a,\ b,\ c,\ d$ "of order unity"

Couplings in the physical bases

$$\mathcal{L}_1 = g_U(\bar{u}_L \gamma^\mu F^U \nu_L + \bar{d}_L \gamma^\mu F^D e_L) U_\mu + \text{h.c}$$

and similar for $\mathcal{L}_{2,3}$

$$F^U = \begin{pmatrix} V_{ub}(s_l \epsilon_l) A_u & V_{ub}(c_l \epsilon_l) A_u & V_{ub}(1-a) r_u \\ V_{cb}(s_l \epsilon_l) A_u & V_{cb}(c_l \epsilon_l) A_u & V_{cb}(1-a) r_u \\ V_{tb}(s_l \epsilon_l)(b-1) & V_{tb}(c_l \epsilon_l)(b-1) & V_{tb} \end{pmatrix}$$

$$F^D = \begin{pmatrix} V_{td}(s_l \epsilon_l) A_d & V_{td}(c_l \epsilon_l) A_d & V_{td}[1-(1-a) r_u] \\ V_{ts}(s_l \epsilon_l) A_d & V_{ts}(c_l \epsilon_l) A_d & V_{ts}[1-(1-a) r_u] \\ V_{tb}(s_l \epsilon_l)(b-1) & V_{tb}(c_l \epsilon_l)(b-1) & V_{tb} \end{pmatrix}$$

in terms of ϵ_l, θ_l and 4 O(1) coefficients

Tree level effects

In terms of $$(R_U, R_{\vec{U}}, R_{\vec{S}}) = \frac{4M_W^2}{g^2}\left(\frac{g_U^2}{M_U^2}, \frac{g_{\vec{U}}^2}{M_{\vec{U}}^2}, \frac{g_{\vec{S}}^2}{M_{\vec{S}}^2}\right)$$

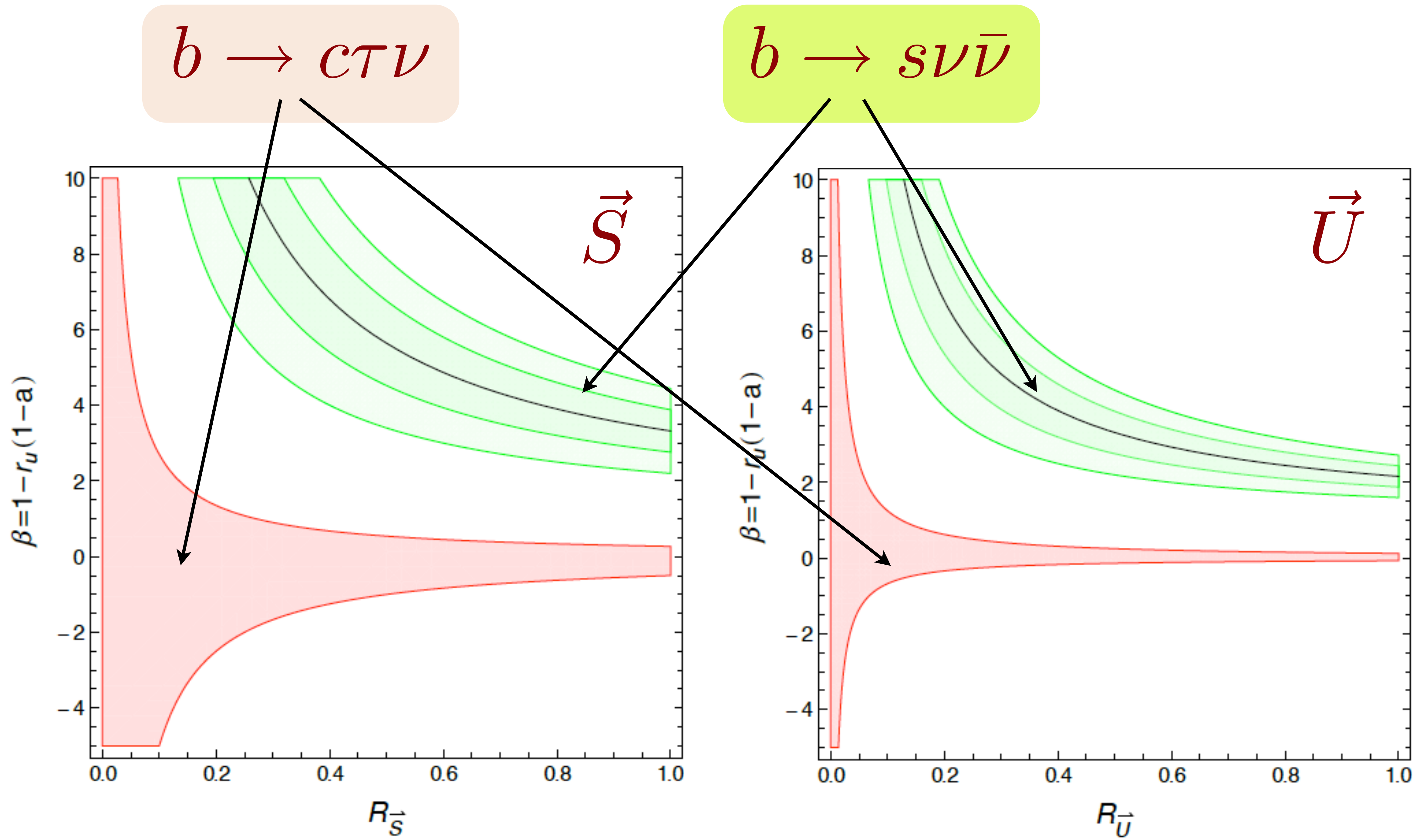
$b \longrightarrow c\tau\nu$

$$R_{D^{(*)}}^{\tau/l} \approx 1 + (R_U, -\frac{1}{4}R_{\vec{U}}, -\frac{1}{8}R_{\vec{S}})r_u(1-a)$$

$b \longrightarrow s\nu\bar{\nu}$

$$R_{K^{(*)}\nu} = \frac{\mathcal{B}(\bar{B} \to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(\bar{B} \to K^{(*)}\nu\bar{\nu})_{SM}} \approx \frac{1}{3}\Big(3 + 2\mathrm{Re}(x) + |x|^2\Big)$$

$$(x_U, x_{\vec{U}}, x_{\vec{S}}) = -\frac{\pi}{\alpha c_\nu^{SM}}[1 - r_u(1-a)]\Big(0, -\frac{R_{\vec{U}}}{2}, \frac{R_{\vec{S}}}{8}\Big)$$



⇒ Only U_μ survives tree level test (trivially)

From U_μ exchange

$$R_K^{\mu/e} = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} = 1 + \left(\frac{2\pi}{\alpha C_9^{SM}}\right)[(b-1)A_d]R_U\epsilon_l^2(1-2s_l^2)$$

Loop effects 1

Based on

$$\mathcal{L}_U = -\frac{1}{2}U^\dagger_{\mu\nu}U^{\mu\nu} + M_U^2 U^\dagger_\mu U_\mu + \mathcal{L}_{an}$$

where

$$U_{\mu\nu} = D_\nu U_\mu - D_\nu U_\mu \qquad D_\mu \equiv \partial_\mu - ig_s\frac{\lambda^a}{2}G^a_\mu - ig'\frac{2}{3}B_\mu$$

$$\mathcal{L}_{an} = -ig_s k_s (U^\dagger_\mu \frac{\lambda^a}{2}U_\nu)G^{\mu\nu^a} - ig'\frac{2}{3}k_Y U^\dagger_\mu U_\nu B^{\mu\nu}$$

(gauge invariant under $SU_{3,2,1}$ for any k_Y, k_s)

and a cutoff Λ taken at $\approx 4\pi M_U/g_U$

Loop effects 2

Vac. pol. $$\Pi^{BB}_{\mu\nu} = i g_{\mu\nu}\Big[-k_Y^2 \frac{(4/9)g'^2}{64\pi^2}\frac{q^4}{M_U^2}\frac{\Lambda^2}{M_U^2}\Big]$$

Vertices $$\mathcal{M}_{B\to L_3\bar{L}_3} = -i3k_Y \frac{(2/3)g'}{64\pi^2} g_U^2 \frac{q^2}{M_U^2}\frac{\Lambda^2}{M_U^2}\epsilon_\mu(\bar{u}_{L3}\gamma_\mu P_L v_{L3})$$

Box diagrams $$\mathcal{L} = \sum_a F_a W_a \frac{g_U^4}{64\pi^2}\frac{\Lambda^2}{M_U^4} O_a$$

	O_a	F_a	W_a
$b\to s\nu_3\bar{\nu}_3$	$(\bar{s}\gamma^\mu P_L b)(\bar{\nu}_3\gamma_\mu P_L \nu_3)$	$[1-(1-a)r_u]$	$V_{tb}V^*_{ts}$
$s\to d\nu_3\bar{\nu}_3$	$(\bar{d}\gamma^\mu P_L s)(\bar{\nu}_3\gamma_\mu P_L \nu_3)$	$[1-(1-a)r_u]^2$	$V_{ts}V^*_{td}$
$b\bar{s}\to\bar{b}s$	$(\bar{s}\gamma^\mu P_L b)^2$	$[1-(1-a)r_u]^2$	$(V_{tb}V^*_{ts})^2$

Dipoles $$\mathcal{L} = \sum_a F_a \frac{g_U^2}{32\pi^2 M_U^2}(1-k_Y)\mathrm{Log}\Big(\frac{\Lambda^2}{M_U^2}\Big) O_a$$

$$\mathcal{O}_{\tau\mu\gamma} = e m_\tau(\bar{\mu}_L\sigma^{\alpha\beta}\tau_R)F_{\alpha\beta}\ , \qquad F_{\tau\mu} = (b-1)(c_l\epsilon_l)$$

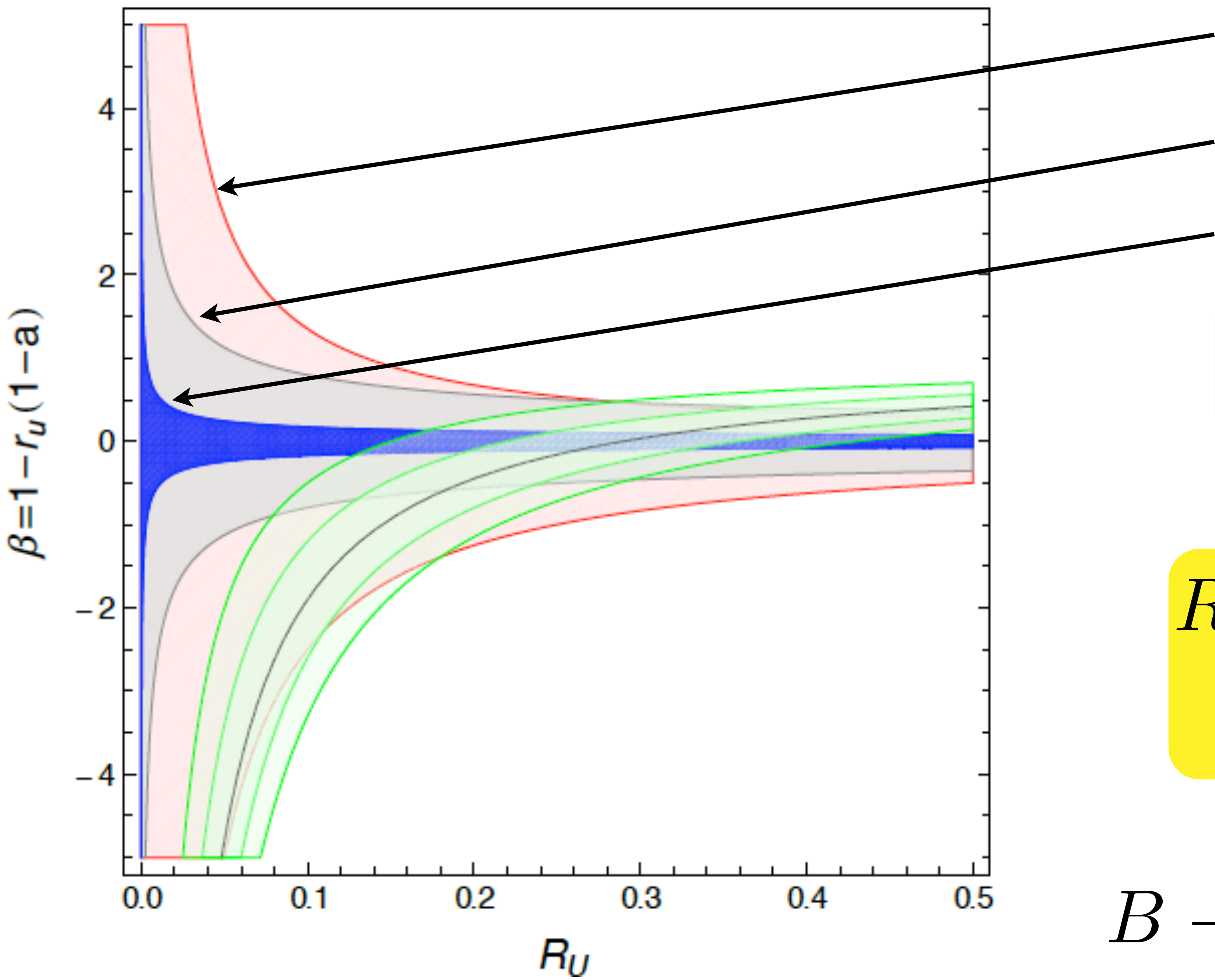
$$\mathcal{O}_{\mu e\gamma} = e m_\mu(\bar{e}_L\sigma^{\alpha\beta}\mu_R)F_{\alpha\beta}\ , \qquad F_{\mu e} = (b-1)^2(c_l\epsilon_l)(s_l\epsilon_l)$$

Consistency with data (and expected signals) 1

EWPT: No S,T,U $\Rightarrow$ mild bound on k_Y

$Z \to \tau\bar{\tau}(b\bar{b}) \Rightarrow \quad k_Y \lesssim 3 \cdot 10^{-2} g_U^2/gg'$

$b \to c\tau\nu$ and correlated processes



$R^{\tau/l}_{D^{(*)}}(b \to c\tau\nu)$

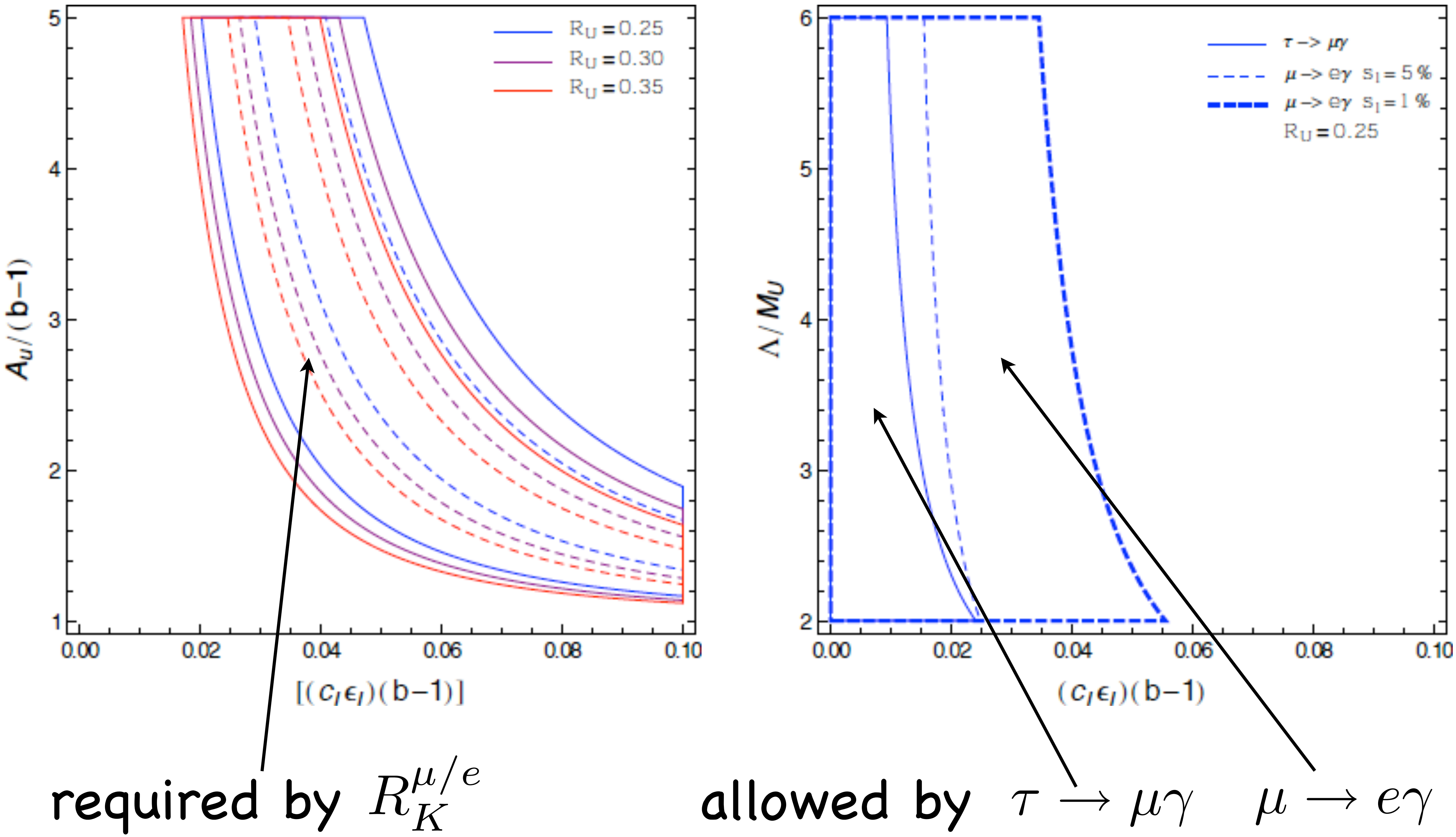
$\Downarrow$

$$R_U = 4g_U^2 M_W^2/g^2 M_U^2 \approx 0.2 \div 0.3$$

$B \to K\tau\bar{\tau} \quad R_K^{\tau/\mu} \approx 1 \div 10$

Consistency with data (and expected signals) 2

$b \to s\mu\bar{\mu}$ and correlated processes



required by $R_K^{\mu/e}$

allowed by $\tau \to \mu\gamma$ $\mu \to e\gamma$

Consistency with data (and expected signals) 3

Leptoquark searches at LHC

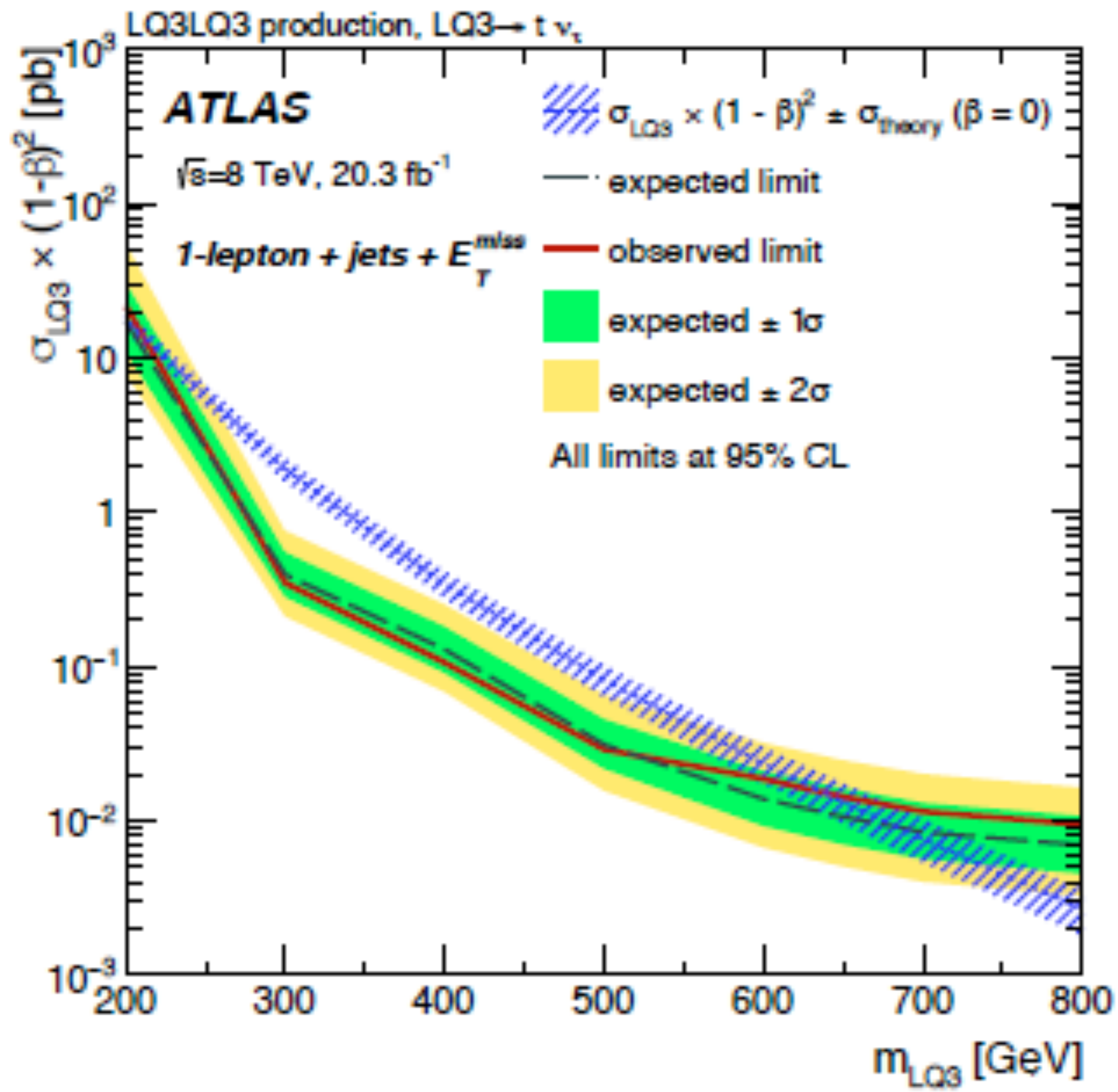
$$gg \to U_\mu U_\mu$$

$$\mathcal{B}(U \to t\bar{\nu}_3) \approx \mathcal{B}(U \to b\,\bar{\tau}) \approx 1/2$$

$$\Gamma_{\rm tot} = g_U^2 M_U/(12\pi)$$

$$\Rightarrow \quad M_U > 770\ GeV$$

$$(R_U > 0.2 \Rightarrow g_U > 1.4)$$



The phenomenological model passes the tests but cries out for a UV completion

A naive sketch

A strong sector with a global $SU(4) \times SO(5)$

$\Rightarrow$ Composite vectors in adjoint of $SU(4) \times SO(4)$

in $SU(4)$: $G_\mu + X_\mu + U_\mu + U_\mu^+$

Composite fermions in

$$\Psi = (4,2,2)_{1/2} \oplus (4,2,2)_{-1/2} \oplus (4,1,1)_{1/2} \oplus (4,1,1)_{1/2}$$

If $M_{V_i} \approx g^* f$ then

$g_U \lesssim g^*$ $\qquad R_U \lesssim (V/f)^2$

Conclusion

Let us see if the anomalies

get reinforced or fade away

e.g. from the LHCb program

- not only R_K ($B \to Ke^+e^-/B \to K\mu^+\mu^-$) but similar ratios with different hadronic systems (K^*, φ, Λ, etc.)
- not only $D^*\tau\nu$, but also $D\tau\nu$, $D_s\tau\nu$, $\Lambda_c\tau\nu$, etc.
  - also trying hadronic tau decays

If they are roses ...

take seriously the leptoquark and $U(2)^5$

Weak MFV

$$U(2)_Q \times U(2)_u \times U(2)_d \times U(1)_{d3}$$

$$y_b = (1,1,1)_{-1} \quad \lambda_u = (2,\bar{2},1)_0 \quad \lambda_d = (2,1,\bar{2})_0 \quad \mathbf{V} = (2,1,1)_0$$

$$\Rightarrow \quad Y_u = \left(\begin{array}{c|c} \lambda_u & y_t x_t \mathbf{V} \\ \hline 0 & y_t. \end{array}\right) \qquad Y_d = \left(\begin{array}{c|c} \lambda_d & y_b x_b \mathbf{V} \\ \hline 0 & y_b \end{array}\right) \quad \mathbf{V} = \begin{pmatrix} 0 \\ \epsilon \end{pmatrix} \quad \lambda_{u,d} = U^{(12)}_{u,d} \lambda^D_{u,d}$$

$$Y_u \approx U_u Y_u^D \qquad Y_d \approx U_d Y_d^D \qquad U_{u,d} \approx U^{(23)}_{u,d}(x_{t,b}\epsilon) U^{(12)}_{u,d}(s_L^{u,d})$$

$$V_{CKM} = U_u^+ U_d = \begin{pmatrix} c_L^u c_L^d & \lambda & s_L^u s\, e^{-i\delta} \\ -\lambda & c_L^u c_L^d & c_L^u s \\ -s_L^d s\, e^{i(\delta+\phi)} & -c_L^d s & 1 \end{pmatrix} \qquad \begin{array}{rcl} s & \sim & O(\epsilon) \\ s_L^u c_L^d - s_L^d c_L^u e^{i\phi} & = & \lambda e^{i\delta} \end{array}$$

$$A(d_i \to d_j) = V_{tj} V_{ti}^* A_{SM}^{\Delta F=1} (1 + (a_{1b}, a_{1s}) (\frac{4\pi M_W}{\Lambda})^2)$$

$$M_{ij} = (V_{tj} V_{ti}^*)^2 A_{SM}^{\Delta F=2} (1 + (a_{2b}, a_{2s}) (\frac{4\pi M_W}{\Lambda})^2)$$