$R_{D^{(*)}}$ and other Flavor Anomalies

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Outline of Talk

- In recent times there have been some anomalies in B decays that indicate lepton non-universal new physics.
- These are in semileptonic $b \to c\tau\bar{\nu_\tau}$ transitions: $R_{D^{(*)}}$ puzzle.
- These are in semileptonic $b \to s\ell\ell$ transitions: P_5' and R_K puzzles.
- There are also other anomalies involving the muons- the $(g-2)_\mu$ and the proton charge radius fro muonic hydrogen.

Outline of Talk

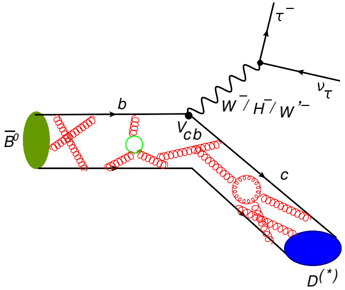
- Discuss $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$ can further constrain NP parameter space in $R_{D^{(*)}}$.

- I will focus on simultaneous explanation of the $R_{D^{(*)}}$ and R_K anomalies.

- Recent work shows how future measurements can distinguish among the models.

- Possible connection between R_K, $(g-2)_\mu$ and large neutrino NSI.

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



$$A_{SM} = \frac{G_F}{\sqrt{2}} V_{cb} \left[\langle D^{(*)}(p') | \bar{c}\gamma^\mu (1-\gamma_5) b | \bar{B}(p) \rangle \right] \bar{\tau}\gamma_\mu (1-\gamma_5)\nu_\tau$$

$$R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+\ell^-\bar{\nu}_\ell)} \qquad R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell)}.$$

Model independent NP analysis (See for example: Datta, Duraisamy, Ghosh)

- Effective Hamiltonian for $b \to c l^- \bar{\nu}_l$ with Non-SM couplings

$$\mathcal{H}_{eff} = \frac{4 G_F V_{cb}}{\sqrt{2}} \Big[(1 + V_L) \, [\bar{c} \gamma_\mu P_L b] \, [\bar{l} \gamma^\mu P_L \nu_l] + V_R \, [\bar{c} \gamma^\mu P_R b] \, [\bar{l} \gamma_\mu P_L \nu_l]$$

$$+ S_L \, [\bar{c} P_L b] \, [\bar{l} P_L \nu_l] + S_R \, [\bar{c} P_R b] \, [\bar{l} P_L \nu_l] + T_L \, [\bar{c} \sigma^{\mu\nu} P_L b] \, [\bar{l} \sigma_{\mu\nu} P_L \nu_l] \Big]$$

Helicity Amplitudes

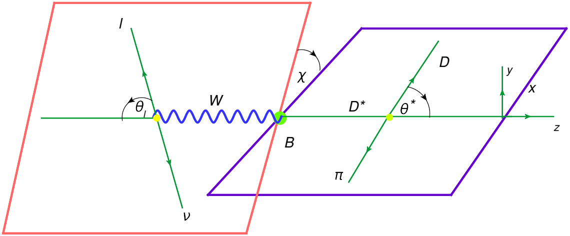
In $\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau$ and $\bar{B} \to D^+\tau^-\bar{\nu}_\tau$ decays we can think of the decay as product of Hadronic and Leptonic Helicity amplitudes.

$$\begin{aligned} A_{SM} &= H_\mu L^\mu = H_\mu g^{\mu\nu} L_\nu \\ &= \sum_\lambda \left[H_\mu \epsilon^\mu_\lambda\right]\left[L_\nu \epsilon^\nu_\lambda\right] \\ &= \sum_\lambda H_\lambda L_\lambda \\ &= \sum_\lambda Amp(B \to D^{(*)} W^*_\lambda) \times Amp(W^*_\lambda \to \ell \bar{\nu}_\ell) \end{aligned}$$

NP modify the SM helicity amplitudes and adds new helicity amplitudes(Scalar, Pseudoscalar, Tensor).

$B \to D^{(*)}\tau\nu_\tau$ in SM

The helicity amplitudes and consequently the NP couplings can be extracted from an angular distribution and compared with models.



If we observe τ decay then we can measure τ polarization.

Interesting Facts

-

$$
\begin{aligned}
R_D^{Ratio} &= \frac{R(D)_{exp}}{R(D)_{SM}} = 1.30 \pm 0.17, \\
R_{D^*}^{Ratio} &= \frac{R(D^*)_{exp}}{R(D^*)_{SM}} = 1.25 \pm 0.08.
\end{aligned}
$$

- If NP is just $V - A$ then

$$
R_D^{\rm ratio} \equiv \frac{R_D^{expt}}{R_D^{SM}} = |1 + V_L|^2 = R_{D^*}^{\rm ratio} \equiv \frac{R_{D^*}^{expt}}{R_{D^*}^{SM}} \ .
$$

- In this case the distributions are just scaling of the SM distributions.

Other Decays: $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$ Measurements

- NP can be constrained from other processes: $B_c \to \tau^- \bar{\nu}_\tau, J/\psi \tau^- \bar{\nu}_\tau$, $b \to \tau \nu X$(LEP), $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$ decays have the same quark transition as $R_{D^{(*)}}$.

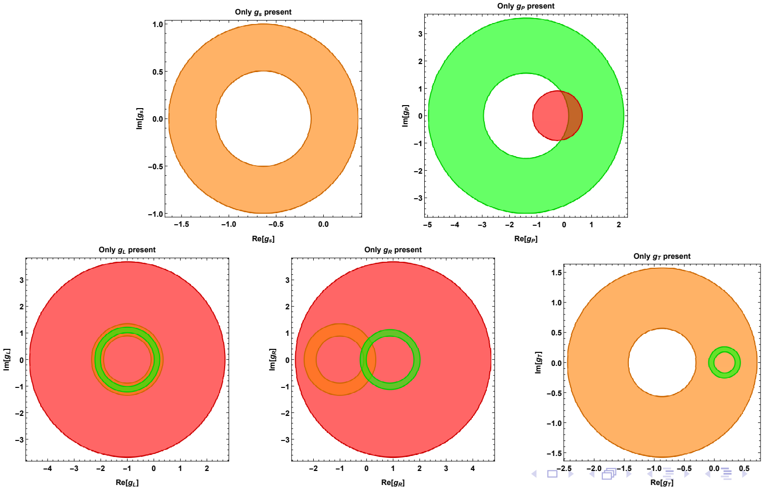
- Measurements in $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$ can further constrain the NP parameter space. (Datta:2017aue, Shivashankara:2015cta).

$$
\begin{aligned}
R(\Lambda_c) &= \frac{\mathcal{B}[\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau]}{\mathcal{B}[\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell]} \\
R^{Ratio}_{\Lambda_c} &= \frac{R(\Lambda_c)^{SM+NP}}{R(\Lambda_c)^{SM}}.
\end{aligned}
$$

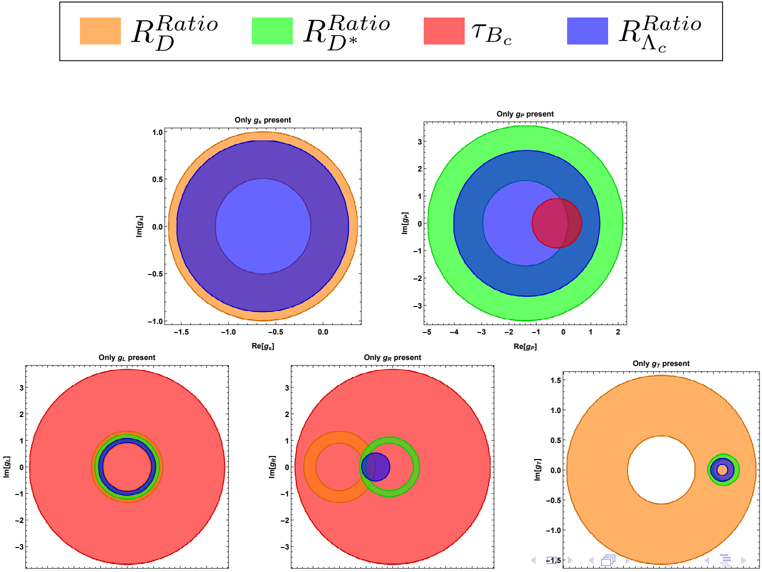
- $\Lambda_b \to \Lambda_c$ form factors are calculated from lattice QCD (Datta:2017aue, Detmold:2015aaa).

Constraints from B Decays

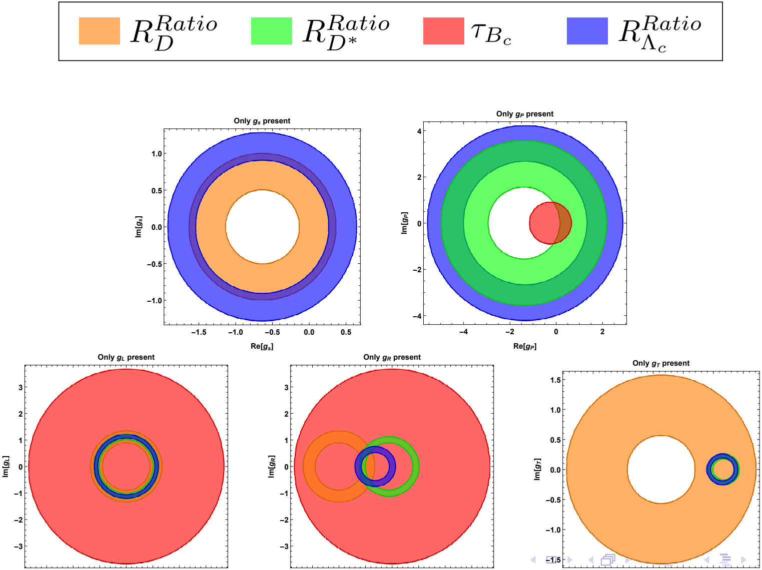
R_D^{Ratio} $R_{D^*}^{Ratio}$ τ_{B_c}



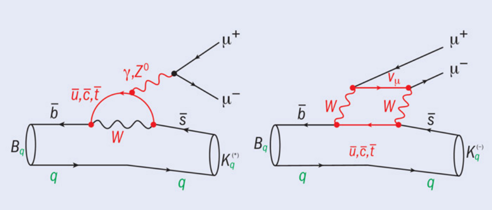
$R_{\Lambda_c}^{Ratio} = 1.0 \pm 3 \times 0.05$



$R_{\Lambda_c}^{Ratio} = 1.3 \pm 3 \times 0.05$



$b \to s\mu^+\mu^-$ Anomaly



$$
\begin{aligned}
H_{\rm eff}(b \to s\ell\bar{\ell}) &= -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}V_{ts}^* \left[C_9 \left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\ell}\gamma_\mu \ell\right) \right. \\
&\qquad \left. + C_{10} \left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\ell}\gamma_\mu\gamma^5 \ell\right)\right] , \\
H_{\rm eff}(b \to s\nu\bar{\nu}) &= -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}V_{ts}^* \, C_L \left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\nu}\gamma_\mu(1-\gamma^5)\nu\right) , \\
H_{\rm eff}(b \to c\ell\bar{\nu}) &= \frac{4G_F}{\sqrt{2}} V_{cb} C_V \left(\bar{c}_L\gamma^\mu b_L\right)\left(\bar{\ell}_L\gamma_\mu \nu_L\right) .
\end{aligned}
$$

P_5' in $B_d^0 \to K^* \mu^+ \mu^-$

$$
\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}
&= \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_k + F_{\mathrm{L}}\cos^2\theta_k \\
&\quad +\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_k\cos 2\theta_l \\
&\quad -F_{\mathrm{L}}\cos^2\theta_k\cos 2\theta_l + S_3\sin^2\theta_k\sin^2\theta_l\cos 2\phi \\
&\quad +S_4\sin 2\theta_k\sin 2\theta_l\cos\phi + S_5\sin 2\theta_k\sin\theta_l\cos\phi \\
&\quad +\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_k\cos\theta_l + S_7\sin 2\theta_k\sin\theta_l\sin\phi \\
&\quad +S_8\sin 2\theta_k\sin 2\theta_l\sin\phi + S_9\sin^2\theta_k\sin^2\theta_l\sin 2\phi\Big].
\end{aligned}
\tag{1}
$$

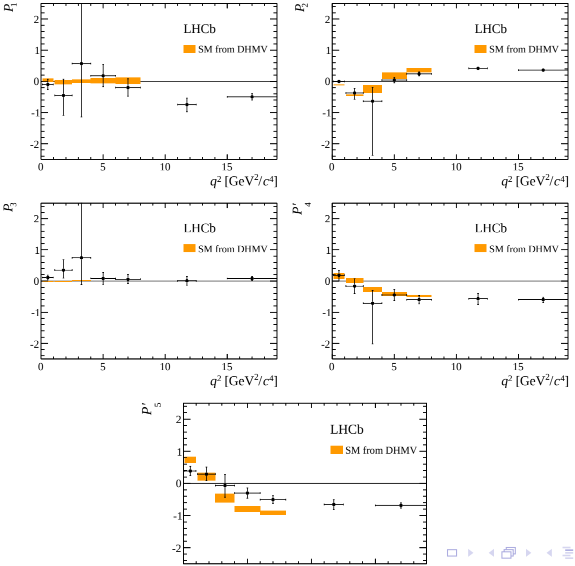
Optimal observables. When E_K is large, small q^2, in leading order in SCET these observables are free from form factors. Corrections are $\sim O(\frac{1}{E_K})$.

$$E_{K^{(*)}} = \frac{m_B^2 + m_{K^{(*)}}^2 - q^2}{2m_B} \quad E_{K^{(*)}} \sim m_B,$$

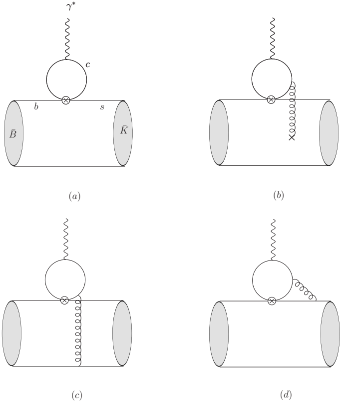
when q^2 small.

$$\begin{aligned} P_1 &= \frac{2\,S_3}{(1-F_{\rm L})} = A_{\rm T}^{(2)}\,, \\ P_2 &= \frac{2}{3}\frac{A_{\rm FB}}{(1-F_{\rm L})}\,, \\ P_3 &= \frac{-S_9}{(1-F_{\rm L})}\,, \\ P'_{4,5,8} &= \frac{S_{4,5,8}}{\sqrt{F_{\rm L}(1-F_{\rm L})}}\,, \\ P'_6 &= \frac{S_7}{\sqrt{F_{\rm L}(1-F_{\rm L})}}\,. \end{aligned} \tag{2}$$

LHCb and Belle



Charm Loop effects: eprint: 1006.4945



Even away from the resonance region there are diagrams with the soft-gluon are suppressed by $\frac{\Lambda^2_{QCD}}{m_c^2}$ when $q^2 << 4m_c^2$. These are the unknown power corrections.

R_K puzzle

- R_K: The LHCb Collaboration has found a hint of lepton non-universality. They measured the ratio $R_K \equiv \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$ in the dilepton invariant mass-squared range 1 GeV$^2 \le q^2 \le 6$ GeV^2 and found

$$R_K^{expt} = 0.745^{+0.090}_{-0.074}\ (\mathrm{stat}) \pm 0.036\ (\mathrm{syst})\ .$$

  This differs from the SM prediction of $R_K^{SM} = 1 \pm O(10^{-4})$ by 2.6σ, and is referred to as the R_K puzzle.
- This measurement is theoretically clean. Several models for the P_5' anomaly can also explain R_K.

- There are several fits to NP for all the $b \to s\ell^+\ell^-$ observables (Descotes-Genon:2015uva, ...). Perform a model-independent analysis of $\bar{b} \to \bar{s}\ell^+\ell^-$, considering NP operators of the form $(\bar{s}\mathcal{O}b)(\bar{\ell}\mathcal{O}'\ell)$, where $\mathcal{O}$ and $\mathcal{O}'$ span all Lorentz structures.

- One of the preferred operator that can reproduce the experimental value of R_K and other observation is of $(V-A)\times(V-A)$ form: $(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}_L\gamma^\mu\ell_L)$. This corresponds to $\Delta C_9^\mu = -\Delta C_{10}^\mu$

- Remember in the $R_{D^{(*)}}$ puzzle also indicated LH NP interactions.

- This gives a hint to connect the two anomalies.

LFV from LUV

- Glashow, Guadagnoli and Lane (GGL) stressed that the NP responsible for lepton flavor non-universality will generally also lead to lepton-flavor-violating (LFV) effects.

$$\frac{G}{\Lambda_{NP}^2}(\bar{b}'_L\gamma_\mu b'_L)(\bar{\tau}'_L\gamma^\mu\tau'_L) \ ,$$

  where $G = O(1)$, $G/\Lambda_{NP}^2 \ll G_F$

- When one transforms to the mass basis, this generates the operator $(\bar{b}_L\gamma_\mu s_L)(\bar{\mu}_L\gamma^\mu\mu_L)$ that contributes to $\bar{b} \to \bar{s}\mu^+\mu^-$. The contribution to $\bar{b} \to \bar{s}e^+e^-$ is much smaller, leading to a violation of lepton flavor universality. GGL's point was that LFV decays, such as $B \to K\mu e$, $K\mu\tau$ and $B_s^0 \to \mu e$, $\mu\tau$, are also generated.

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

Assuming the scale of NP is much larger than the weak scale, the operator of GGL should be made invariant under the full $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group (Alonso, Grinstein, Camalich). (Bhattacharya, Datta, London, Shivshankara) considered two possibilities:

$$
\begin{aligned}
\mathcal{O}_1^{NP} &= \frac{G_1}{\Lambda_{NP}^2}(\bar{Q}'_L\gamma_\mu Q'_L)(\bar{L}'_L\gamma^\mu L'_L)\ , \\
\mathcal{O}_2^{NP} &= \frac{G_2}{\Lambda_{NP}^2}(\bar{Q}'_L\gamma_\mu\sigma^I Q'_L)(\bar{L}'_L\gamma^\mu\sigma^I L'_L) \\
&= \frac{G_2}{\Lambda_{NP}^2}\left[2(\bar{Q}'^i_L\gamma_\mu Q'^j_L)(\bar{L}'^j_L\gamma^\mu L'^i_L) - (\bar{Q}'_L\gamma_\mu Q'_L)(\bar{L}'_L\gamma^\mu L'_L)\right]\ .
\end{aligned}
$$

Here $Q' \equiv (t', b')^T$ and $L' \equiv (\nu'_\tau, \tau')^T$. The key point is that $\mathcal{O}_2^{NP}$ contains both neutral-current (NC) and charged-current (CC) interactions. The NC and CC pieces can be used to respectively explain the R_K and $R_{D^{(*)}}$ puzzles.

UV completion

Crevellin considered possible UV completions that can give rise to $\mathcal{O}_{1,2}^{NP}$

- (i) a vector boson (VB) that transforms as $(\mathbf{1}, \mathbf{3}, 0)$ under $SU(3)_C \times SU(2)_L \times U(1)_Y$, as in the SM,
- (ii) an $SU(2)_L$-triplet scalar leptoquark (S_3) $[(\mathbf{3}, \mathbf{3}, -2/3)$.
- (iii) an $SU(2)_L$-singlet vector leptoquark (U_1) $[(\mathbf{3}, \mathbf{1}, 4/3)$.
- $SU(2)_L$-triplet vector leptoquark (U_3) $[(\mathbf{3}, \mathbf{3}, 4/3)]$
- The vector boson generates only $\mathcal{O}_2^{NP}$, but the leptoquarks generate particular combinations of $\mathcal{O}_1^{NP}$ and $\mathcal{O}_2^{NP}$.

Couplings

The four models contribute differently to $\mathcal{O}_1^{NP}$ and $\mathcal{O}_2^{NP}$:

$$
\begin{aligned}
VB &: \quad g_1 = 0 \;, \quad g_2 = -g_{qV}^{33} g_{\ell V}^{33} \quad , \qquad g_2 \text{ can be positive or negative} \;, \\
S_3 &: \quad g_1 = 3g_2 = \frac{3}{4}|h_{S_3}^{33}|^2 > 0 \;, \\
U_1 &: \quad g_1 = g_2 = -\frac{1}{2}|h_{U_1}^{33}|^2 < 0 \;, \\
U_3 &: \quad g_1 = -3g_2 = -\frac{3}{2}|h_{U_3}^{33}|^2 < 0 \;.
\end{aligned}
$$

Models: Bhattacharya, Datta, Guevin, London, Watanabe

Transform to the mass basis:

$$u'_L \;=\; Uu_L\ ,\ \ d'_L = Dd_L\ ,\ \ \ell'_L = L\ell_L\ ,\ \ \nu'_L = L\nu_L\ ,$$

The CKM matrix is given by $V_{CKM} = U^\dagger D$. The assumption is that the transformations D and L involve only the second and third generations:

$$D \;=\; \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_D & \sin\theta_D \\ 0 & -\sin\theta_D & \cos\theta_D \end{pmatrix}$$

$$L \;=\; \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_L & \sin\theta_L \\ 0 & -\sin\theta_L & \cos\theta_L \end{pmatrix}\ .$$

$$V_{CKM}D^\dagger \;=\; U^\dagger$$

SM-like vector bosons

This model contains vector bosons (VBs) that transform as $(\mathbf{1},\mathbf{3},0)$ under $SU(3)_C \times SU(2)_L \times U(1)_Y$, as in the SM. The coupling is to only third generation. In the gauge basis, the Lagrangian describing the couplings of the VBs to left-handed third-generation fermions is

$$\mathcal{L}_V = g_{qV}^{33} \left(\overline{Q}'_{L3} \, \gamma^\mu \sigma^I \; Q'_{L3} \right) V_\mu^I + g_{\ell V}^{33} \left(\overline{L}'_{L3} \, \gamma^\mu \sigma^I \; L'_{L3} \right) V_\mu^I \, .$$

$$\mathcal{L}_V^{eff} = -\frac{g_{qV}^{33} g_{\ell V}^{33}}{m_V^2} \left(\overline{Q}'_{L3} \gamma^\mu \sigma^I \; Q'_{L3} \right) \left(\overline{L}'_{L3} \gamma_\mu \sigma^I L'_{L3} \right) \; .$$

$$g_1 = 0 \quad , \qquad g_2 = -g_{qV}^{33} g_{\ell V}^{33} \; .$$

The VB model also generates 4 quark and 4 lepton operators that contribute to B_s mixing, $\tau \to \mu\mu\mu$ e.t.c. Variation of this model with more parameters.

- When one transforms to the mass basis, two new parameters are introduced, θ_D, θ_L.
- The NP contributes to $b \to s\mu^+\mu^-$, $b \to s\nu\bar{\nu}$ and $b \to c\tau^-\bar{\nu}$. These contributions are give functions of g_1, g_2, θ_D, θ_L.
- Another decay to which all four models contribute is $\tau \to \mu\phi(\eta, \eta')$.
- In addition, the VB model contributes to other processes, such as B_s^0-$\bar{B}_s^0$ mixing and $\tau \to 3\mu$.
- The experimental measurements of, or limits on, these processes provide constraints on the NP parameter space.

- We fix $\Lambda_{NP} = 1$ TeV and assume a common value for $2g_{qV}^{33} g_{\ell V}^{33}$, $\left|h_{S_3}^{33}\right|^2$, $\left|h_{U_1}^{33}\right|^2$ and $\left|h_{U_3}^{33}\right|^2$.

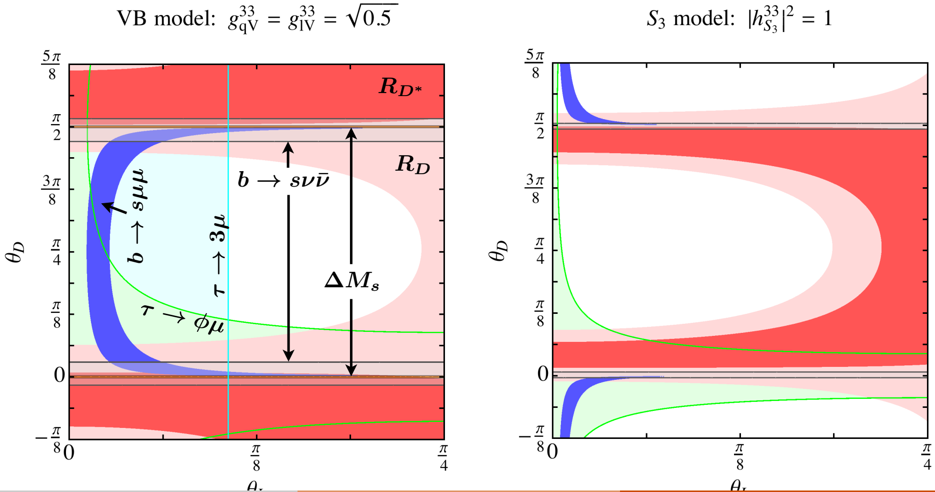
- We apply all the experimental constraints to establish the allowed region in the (θ_D, θ_L) parameter space.

- If there is no region in which all constraints overlap, the model is excluded.

- For the models that are retained, we predict the rates for other processes based on the allowed region in parameter space.

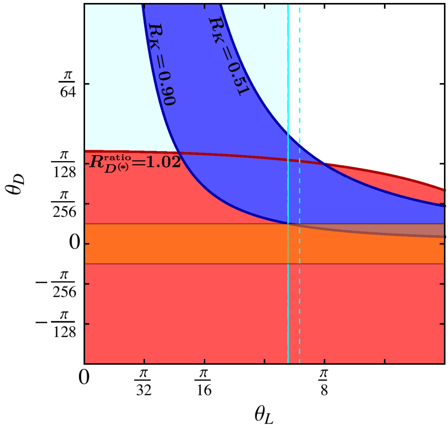
- Since this region can be different for different models, it may be possible to distinguish them.

Models: allowed parameter space: $R_K \sim \sin\theta_D \cos\theta_D \sin^2\theta_L$

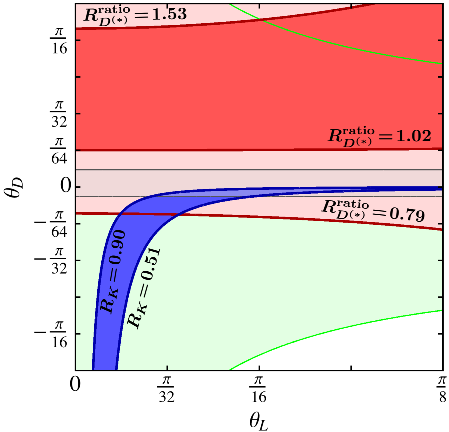


Models: allowed parameter space

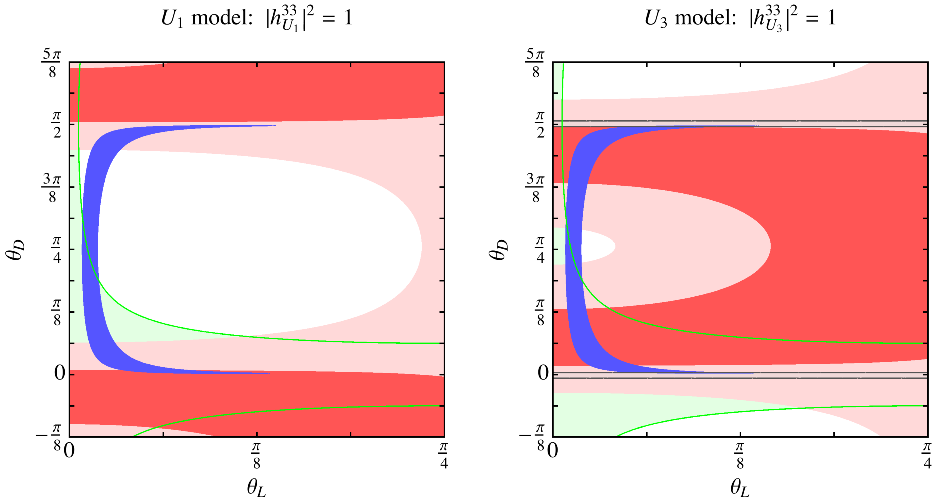
VB model: $g^{33}_{\rm qV} = g^{33}_{\rm lV} = \sqrt{0.5}$



S_3 model: $|h^{33}_{S_3}|^2 = 1$



Models: allowed parameter space



Models: allowed parameter space

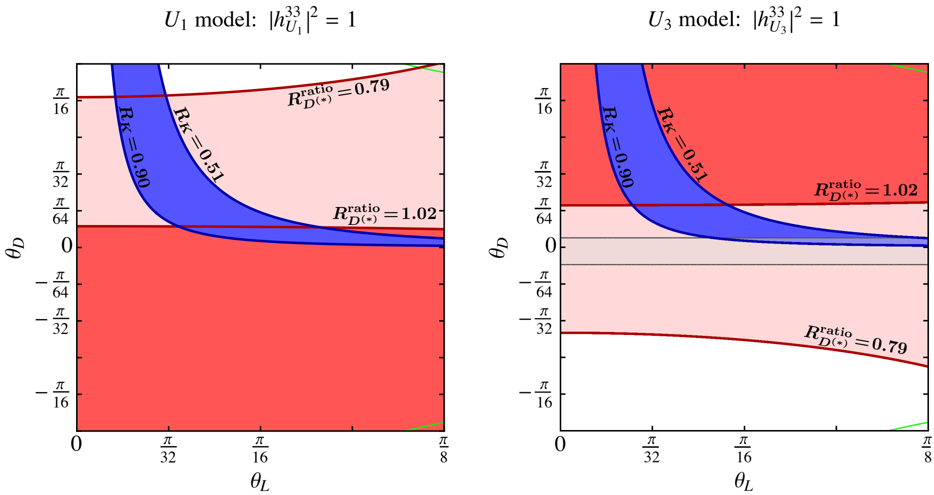


Figure: Magnified figures of Fig. 1. The color legends are the same as the

Direct Search limits

- One can set limits on $g^2/\Lambda_{\rm NP}^2$ from direct searches, assuming a certain mode of production for the new mediator states (Faroughy, Greljo, Kamenik)

- Using the $b\bar{b} \to \tau\bar{\tau}$ process mediated by s- or t-channel vector-boson or leptoquark exchange, one can get the following rough upper bounds:

- $|g_{qV}^{33} g_{\ell V}^{33}|_{\rm max}/\Lambda_{\rm NP}^2 \sim 3$ TeV^{-2} for the VB model

- $\left|h_{U_1}^{33}\right|_{\rm max}^2/\Lambda_{\rm NP}^2 \sim 5$ TeV^{-2} for the U_1 model.

- That is, for $\Lambda_{\rm NP} = 1$ TeV, $g_{qV}^{33} g_{\ell V}^{33} \leq 3$ and $\left|h_{U_1}^{33}\right|^2 \leq 5$

Predictions

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

$$\begin{aligned} VB &\quad : \quad R^{\rm ratio}_{D^{(*)}} \simeq 1.04 \ , \\ U_1 &\quad : \quad 1.02 \le R^{\rm ratio}_{D^{(*)}} \le 1.29 \ . \end{aligned}$$

  If it is found that $1.04 < R_{D^{(*)}} \le 1.29$, this will indicate U_1.

- R_K:

$$\begin{aligned} VB &\quad : \quad R_K \simeq 0.90 \ , \\ U_1 &\quad : \quad 0.51 \le R_K \le 0.90 \ . \end{aligned}$$

  If future measurements find $0.51 \le R_K < 0.90$, this would point clearly to U_1 (and exclude VB).

$\tau \to 3\mu$

This decay is particularly interesting because only the *VB* model contributes to it. The present experimental bound is $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) < 2.1 \times 10^{-8}$ at 90% C.L. . Belle II expects to reduce this limit to $< 10^{-10}$. The reach of LHCb is somewhat weaker, $< 10^{-9}$.

Now, the amplitude for $\tau \to 3\mu$ depends only on θ_L. The allowed value of θ_L corresponds to the present experimental bound. That is, *VB* predicts

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) \simeq 2.1 \times 10^{-8} .$$

Thus, the *VB* model predicts that $\tau \to 3\mu$ should be observed at both LHCb and Belle II. This is a smoking-gun signal for the model.

τ Modes

- $B_s^0 \to \tau^+\tau^-$

$$
\begin{aligned}
VB \quad &: \quad \mathcal{B}(B_s^0 \to \tau^+\tau^-) \simeq 2.4 \times 10^{-7} \ , \\
U_1 \quad &: \quad \mathcal{B}(B_s^0 \to \tau^+\tau^-)|_{\rm max} = 5.4 \times 10^{-4} \ .
\end{aligned}
$$

However, we cannot evaluate whether this decay can be used to distinguish the two models as we do not know the reach of LHCb or Belle II for $B_s^0 \to \tau^+\tau^-$.

- $B \to K^{(*)}\tau^+\tau^-$:

$$
\begin{aligned}
VB \quad &: \quad \mathcal{B}(B \to K^{(*)}\tau^+\tau^-) \simeq 4.4 \times 10^{-8} \ , \\
U_1 \quad &: \quad \mathcal{B}(B \to K^{(*)}\tau^+\tau^-)|_{\rm max} = 1.1 \times 10^{-4} \ .
\end{aligned}
$$

It may just be attainable at Belle II (its reach is $\sim 2 \times 10^{-4}$. Thus, $B \to K^{(*)}\tau^+\tau^-$ could perhaps be used to distinguish the two models.

LFV Decays

- $B \to K^{(*)}\mu\tau$:

$$\begin{aligned} VB &: \quad \mathcal{B}(B \to K^{(*)}\mu\tau) \simeq 4.0 \times 10^{-10} \ , \\ U_1 &: \quad \mathcal{B}(B \to K^{(*)}\mu\tau)|_{\max} = 1.6 \times 10^{-7} \ . \end{aligned}$$

Unfortunately, it is still below the reach of Belle II (which is 5×10^{-7}.

- $B_s^0 \to \mu\tau$:

$$\begin{aligned} VB &: \quad \mathcal{B}(B_s^0 \to \mu\tau) \simeq 6.7 \times 10^{-9} \ , \\ U_1 &: \quad \mathcal{B}(B_s^0 \to \mu\tau)|_{\max} = 2.8 \times 10^{-6} \ . \end{aligned}$$

However, we cannot evaluate whether this decay can be used to distinguish the two models as we do not know the reach of LHCb or Belle II for $B_s^0 \to \mu\tau$.

Υ Modes

- $\Upsilon(3S) \to \mu\tau$:

$$VB \qquad \mathcal{B}(\Upsilon(3S) \to \mu\tau) \simeq 3.0 \times 10^{-9} \, ,$$

$$U_1 \quad : \quad \mathcal{B}(\Upsilon(3S) \to \mu\tau)|_{\rm max} = 8.0 \times 10^{-7} \, .$$

  We made a rough estimate that Belle II should be able to measure $\mathcal{B}(\Upsilon(3S) \to \mu\tau)$ down to $\sim 10^{-7}$. If this decay were seen, it would exclude VB and point to U_1. This demonstrates the importance of this process for testing NP models in B decays.

- Quarkonium Decays to leptons can be used to constrain $R_{D^{(*)}}$ new physics Models (Aloni, Efrati, Grossman,Nir.) .

Light Z' R_K and $g-2$

- (Farzan:2015doa ....) presented a model based $U(1)$ gauge interaction with a gauge boson of mass $m_{Z'} \sim \text{few } 10 \text{ MeV}$ and gauge coupling of $g_{Z'} \sim 10^{-5}$ which couples to the second and third generations of leptons (but not to the electron) as well as to the quarks. This gauge interaction leads to large neutrino NSI.

- B anomalies can be explained by heavy NP with

$$\frac{g^2}{\Lambda^2} \sim \frac{1}{TeV^2} = \frac{10^{-10}}{(10MeV)^2}$$

Coherent forward scattering ($q^2 = 0$) which leads to $O(1)$ NSI corresponds to

$$\frac{g^2}{\Lambda^2} \sim \frac{10^{-10}}{(10MeV)^2}$$

Light Z' Searches

- Constraints: Come from Kaon and pion semileptonic decays with missing energy, Mixing with photon, BBN, Supernova, High Energy Cosmic neutrino(ICECUBE), Neutrino scattering, Neutrino trident production.
- Search; $\mu + A \to \mu + A + Z'$, $Z' \to \nu\bar{\nu}$: Z' can be produced by scattering of muon beam off nuclei and can then decay into a $\nu\bar{\nu}$ pair. There is a proposed experiment using muon beam with energy of 150 GeV from CERN SPS to search for such a signal. It is shown that with 10^{12} incident muons, values of g' as small as 10^{-5} can be probed.

Light Z' R_K and $(g-2)_\mu$ (Datta, Marfatia, Liao)

The most general form of the bsZ' vertex with vector type coupling is

$$H_{bsZ'} = F(q^2)\bar{s}\gamma^\mu b Z'_\mu ,$$

where the form factor $F(q^2)$ can be expanded as

$$F(q^2) = a_{bs} + g_{bs}\frac{q^2}{m_B^2} + \ldots ,$$

where m_B is the B meson mass and the momentum transfer $q^2 \ll m_B^2$. The leading order term a_{bs} is constrained by $B \to K\nu\bar{\nu}$ to be smaller than 10^{-9}. The solution to the R_K puzzle would then require the Z' coupling to muons to be $O(1)$ or larger which is in conflict with the $(g-2)_\mu$ measurement. The absence of flavor-changing neutral currents forces $a_{bs} \sim 0$, so that

$$H_{bsZ'} = g_{bs}\frac{q^2}{m_B^2}\bar{s}\gamma^\mu b Z'_\mu \quad (H_{bsZ'} \sim \bar{s}\gamma^\mu b \partial^\nu Z'_{\mu\nu}) ,$$

where g_{bs} is assumed to be real.

Now we introduce a Z' coupling only to left-handed neutrinos. We write for generation $\alpha = \mu, \tau$,

$$H_{\nu_\alpha \nu_\alpha Z'} \quad = \quad g_{\nu_\alpha \nu_\alpha} \bar{\nu}_{\alpha L} \gamma^\mu \nu_{\alpha L} Z'_\mu \,,$$

The Hamiltonian for $b \to s \nu_\alpha \bar{\nu}_\alpha$ decays,

$$H_{bs\nu_\alpha \nu_\alpha} \quad = \quad -\frac{g_{bs} g^*_{\nu_\alpha \nu_\alpha}}{q^2 - m^2_{Z'}} \frac{q^2}{m_B^2} \bar{s} \gamma^\mu b \bar{\nu}_{\alpha L} \gamma_\mu \nu_{\alpha L} \,.$$

From $B \to K \nu \bar{\nu}$. we obtain the 2σ constraint,

$$|g_{bs}| \lesssim 1.4 \times 10^{-5} \,.$$

Note that this constraint does not dependent on $g_{\nu\nu}$ as the NP contribution is dominated by the two body $b \to s Z'$ transition. The B_s mixing gives

$$|g_{bs}| \quad \lesssim \quad 2.3 \times 10^{-5}.$$

This is consistent with the bound obtained on g_{bs} from $B \to K \nu \bar{\nu}$.

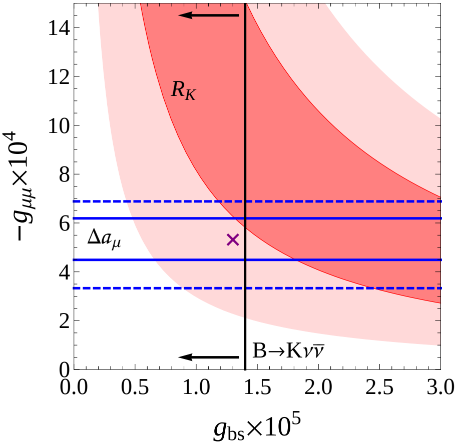
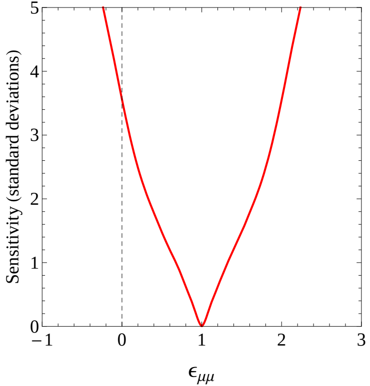


Figure: The allowed regions in the $(g_{bs}, g_{\mu\mu})$ plane for $m_{Z'} = 10$ MeV. The shaded bands are the 1σ and 2σ regions favored by R_K. The regions between the horizontal solid and dashed lines explain the discrepancy in the anomalous magnetic moment of the muon at the 1σ and 2σ C.L. The vertical line shows the 2σ upper limit on g_{bs} from $B \to K\nu\bar{\nu}$. The cross denotes the parameters used for studying neutrino NSI.

- With vector coupling to light quarks the $K-\pi$ puzzle cannot be solved.
- We can fix the coupling of the quarks by requiring the generated $b \to s\bar{q}q$ coupling to be certain fraction of the SM electroweak penguins.
- In this case $|g_{uu} - g_{dd}| \sim 10^{-5}$. We will assume that g_{uu} is the same size as g_{dd} and take these couplings to be $\sim 10^{-5}$ to discuss neutrino NSI.



Conclusions

- Several anomalies in B decays indicating lepton non-universal interactions. Additional anomalies involving muons.
- Several anomalies may arise from the same New Physics.
- Anomalies indicate LUV. In general we should also observe LFV processes.
- Interesting modes are $\tau \to 3\mu$ and $\Upsilon(3S) \to \mu\tau$. Observation of these modes can point to specific models of new physics.
- There may be a connection between R_K, $(g-2)_\mu$ and large neutrino NSI involving $\nu_{\mu,\tau}$.