Puzzles in B Decays

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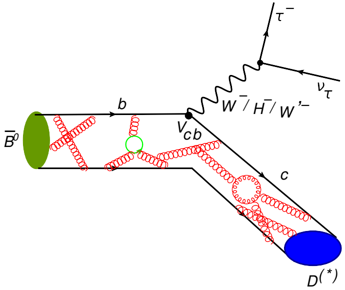
Outline of Talk

- 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 $b \to s\ell^+\ell^-(l = \mu, e)$ transitions: P_5' and R_K, $R_{K^{(*)}}$ puzzles. BR of $b \to s\mu^+\mu^-$ modes are lower.

Outline of Talk

- Recently, LHCb announced LUV in measurement of $R_{K^{(*)}}$
- I will focus on simultaneous explanation of the $R_{D^{(*)}}$ and $R_K, R_{K^{(*)}}$ anomalies.
- Recent work shows how future measurements can distinguish among the models.
- Light new physics: GeV scale or 10-100 MeV mediators.

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



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

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

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

Recently, the BaBar, Belle and LHCb have reported the following measurements :

$$\begin{aligned} R(D) &\equiv \frac{\mathcal{B}(\bar{B}\to D^+\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^+\ell^-\bar{\nu}_\ell)} = 0.440\pm 0.058\pm 0.042\ , \\ R(D^*) &\equiv \frac{\mathcal{B}(\bar{B}\to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^{*+}\ell^-\bar{\nu}_\ell)} = 0.332\pm 0.024\pm 0.018\ . \end{aligned} \tag{1}$$

Belle

$$\begin{aligned} R(D) &\equiv 0.375\pm 0.064\pm 0.026\ , \\ R(D^*) &\equiv 0.293\pm 0.038\pm 0.015\ , 0.302\pm 0.030\pm 0.011\ . \end{aligned} \tag{2}$$

LHCb

$$\begin{aligned} R(D^*) &\equiv 0.336\pm 0.027\pm 0.030\ . \\ R(D^*) &\equiv 0.306\pm 0.016\pm 0.010\ . \end{aligned} \tag{3}$$

Average HFAG

$$\begin{aligned} R(D) &\equiv 0.397 \pm 0.040 \pm 0.028 \\ R(D^*) &\equiv 0.316 \pm 0.016 \pm 0.010. \end{aligned} \tag{4}$$

Theory

$$\begin{aligned} R(D) &\equiv 0.299 \pm 0.011(FNAL/MILC), 0.300 \pm 0.008(HPQCD) \\ &\equiv 0.299 \pm 0.003(arXiv : 1703.05330) \\ R(D^*) &\equiv 0.257 \pm 0.003(arXiv : 1703.05330)\ . \end{aligned} \tag{5}$$

$R(D^*)$ is 3.3 σ from SM. $R(D)$ is 1.9 σ from SM. Combined with co-relations is 4 σ deviation.

$\bar{B} \to D^{(*)} \ell^- \bar{\nu}_\ell$

- In the ratios $R(D^{(*)})$ the form factors effects (largely) cancel, V_{cb} cancels and experimental systematic effects cancel.
- The SM has a flavor symmetry $SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$ in the absence of Yukawa interactions.
- W couples universally to all lepton generations.
- The results imply lepton non-universal interactions.

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

- Effective Hamiltonian for $b \to c l^- \bar{\nu}_l$ with Non-SM couplings. The NP has to be LUV.

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

The NP can be probed via distributions and other related decays.

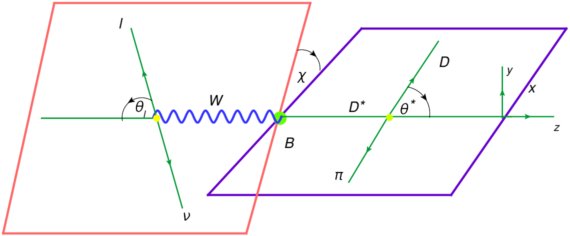
$B \to D^{(*)}\tau\nu_\tau$ in SM + NP, Helicity Amplitudes

Decay Distribution described by Helicity Amplitudes

$$
\begin{aligned}
\mathcal{H}_0 &= \frac{1}{2m_{D^*}\sqrt{q^2}}\Big[(m_B^2 - m_{D^*}^2 - q^2)(m_B + m_{D^*})A_1(q^2) \\
&\quad -\frac{4m_B^2|p_{D^*}|^2}{m_B + m_{D^*}}A_2(q^2)\Big](1 - g_A)\,, \\
\mathcal{H}_\parallel &= \sqrt{2}(m_B + m_{D^*})A_1(q^2)(1 - g_A)\,, \\
\mathcal{H}_\perp &= -\sqrt{2}\frac{2m_B V(q^2)}{(m_B + m_{D^*})}|p_{D^*}|(1 + g_V)\,, \\
\mathcal{H}_t &= \frac{2m_B|p_{D^*}|A_0(q^2)}{\sqrt{q^2}}(1 - g_A)\,, \\
\mathcal{H}_P &= -\frac{2m_B|p_{D^*}|A_0(q^2)}{(m_b(\mu) + m_c(\mu))}g_P\,.
\end{aligned}
$$

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

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



Distribution includes CPV terms which are clean probes of NP without form factor issues. If we observe τ decay then we can measure τ polarization and CPV.

Other Decays

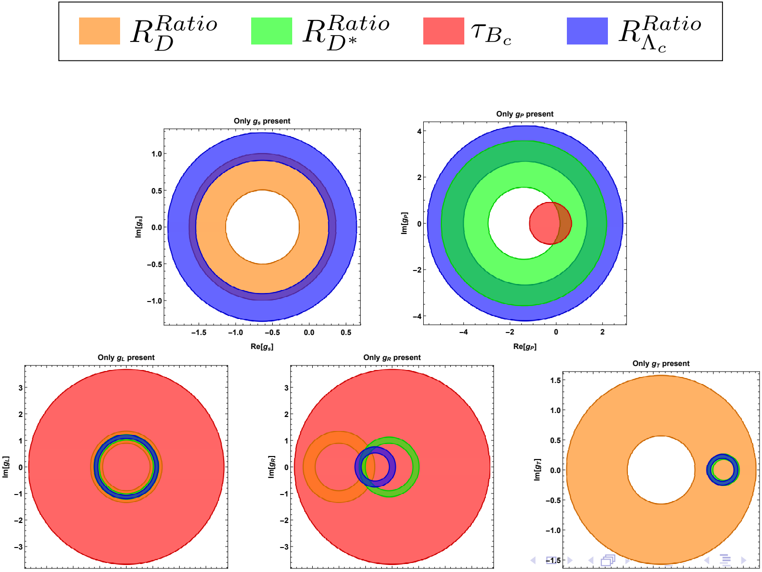
- NP can be constrained from other decays have the same quark transition as $R_{D^{(*)}}$: $B_c \to \tau^- \bar{\nu}_\tau$(Alonso, Grinstein, Camalich) , $B_c \to J/\psi \tau^- \bar{\nu}_\tau$, $b \to \tau \nu X$(LEP), $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$.

- 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).

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



Interesting Facts

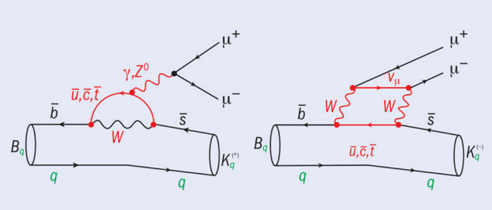
- $$\begin{aligned} R_D^{Ratio} &= \frac{R(D)_{exp}}{R(D)_{SM}} = 1.30 \pm 0.17, \\ R_{D^*}^{Ratio} &= \frac{R(D^*)_{exp}}{R(D^*)_{SM}} = 1.25 \pm 0.08. \end{aligned}$$

- 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.

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



$$
\begin{aligned}
H_{\text{eff}}(b \to s\ell\bar{\ell}) &= -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}V_{ts}^* \left[C_9 \, (\bar{s}_L \gamma^\mu b_L) \left(\bar{\ell}\gamma_\mu \ell\right) \right. \\
&\qquad \left. + \, C_{10} \, (\bar{s}_L \gamma^\mu b_L) \left(\bar{\ell}\gamma_\mu \gamma^5 \ell\right) \right] \ , \\
H_{\text{eff}}(b \to s\nu\bar{\nu}) &= -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb}V_{ts}^* \, C_L \, (\bar{s}_L \gamma^\mu b_L) \left(\bar{\nu}\gamma_\mu (1-\gamma^5)\nu\right) \ , \\
H_{\text{eff}}(b \to s\gamma^*) &= C_7 \, \frac{e}{16\pi^2} \left[\bar{s}\sigma_{\mu\nu}(m_s P_L + m_b P_R) b\right] F^{\mu\nu}
\end{aligned}
$$

Some Facts

- At the m_b scale $C_9 \sim -C_{10} = 4.2$ while $C_7 \sim 0.3$ and so semileptonic operators usually dominate. NP contribution from C_7 is not LUV.
- Low q^2 region is clean. Factorization results hold and Form Factors can satisfy certain symmetry relations(SCET).
- For very low q^2 the photon pole may dominates over the semileptonic operators.
- $b \to s\ell^+\ell^-$ can come from charm resonance. $b \to sJ/\psi(\to \ell\ell)$. So charm resonance region is cut out from measurement.

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

$$
\begin{aligned}
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}
&= \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_k + F_{\mathrm{L}}\cos^2\theta_k \\
&\quad +\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_k\cos 2\theta_l \\
&\quad -F_{\mathrm{L}}\cos^2\theta_k\cos 2\theta_l + S_3\sin^2\theta_k\sin^2\theta_l\cos 2\phi \\
&\quad +S_4\sin 2\theta_k\sin 2\theta_l\cos\phi + S_5\sin 2\theta_k\sin\theta_l\cos\phi \\
&\quad +\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_k\cos\theta_l + S_7\sin 2\theta_k\sin\theta_l\sin\phi \\
&\quad +S_8\sin 2\theta_k\sin 2\theta_l\sin\phi + S_9\sin^2\theta_k\sin^2\theta_l\sin 2\phi\Big].
\end{aligned}
\tag{6}
$$

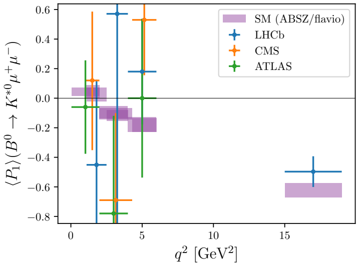
Optimal observables. When E_K is large, small q^2, in leading order in SCET these observables are free from form factors. Corrections are $\sim O(\frac{1}{E_K})$.

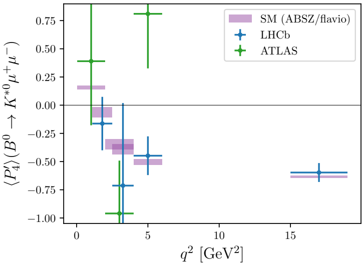
$$E_{K^{(*)}} = \frac{m_B^2 + m_{K^{(*)}}^2 - q^2}{2m_B} \quad E_{K^{(*)}} \sim m_B,$$

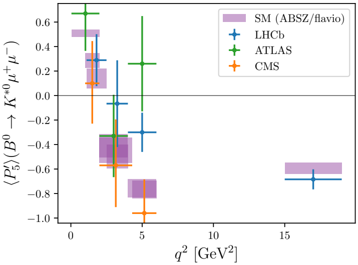
when q^2 small.

$$\begin{aligned}
P_1 &= \frac{2\,S_3}{(1-F_{\rm L})} = A_{\rm T}^{(2)}\,, \\
P_2 &= \frac{2}{3}\frac{A_{\rm FB}}{(1-F_{\rm L})}\,, \\
P_3 &= \frac{-S_9}{(1-F_{\rm L})}\,, \\
P'_{4,5,8} &= \frac{S_{4,5,8}}{\sqrt{F_{\rm L}(1-F_{\rm L})}}\,, \\
P'_6 &= \frac{S_7}{\sqrt{F_{\rm L}(1-F_{\rm L})}}\,.
\end{aligned} \tag{7}$$

LHC


SM (ABSZ/flavio)
LHCb
CMS
ATLAS
$\langle P_1 \rangle (B^0 \to K^{*0}\mu^+\mu^-)$
q^2 [GeV^2]


SM (ABSZ/flavio)
LHCb
ATLAS
$\langle P_4' \rangle (B^0 \to K^{*0}\mu^+\mu^-)$
q^2 [GeV^2]


SM (ABSZ/flavio)
LHCb
ATLAS
CMS
$\langle P_5' \rangle (B^0 \to K^{*0}\mu^+\mu^-)$
q^2 [GeV^2]

NP Explanation

- Effective theory :Fits to NP semileptonic operators.
- 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 (Descotes-Genon, Matias, Virto, arXiv:1307.5683). NP in $\Delta C_{9\mu}$
- Can come from Z' models or Leptoquark Models.
- Can be induced by four quark operators.

Four quark operators, Datta, Duraisamy, Ghosh, 1310.1937

Some NP (e.g. Top Color) through new particle exchange generates the following operators

$$\mathcal{H}_{\rm eff}^{\rm NP} \sim \frac{\mathcal{A}_1}{\Lambda^2}\overline{b}'\,(1+\gamma_5)\,b'\;\overline{b}'\,(1-\gamma_5)\,b' + \frac{\mathcal{A}_1}{\Lambda^2}\overline{b}'\,(1-\gamma_5)\,b'\;\overline{b}'\,(1+\gamma_5)\,b'\;,$$

Go from gauge to mass basis and

$$\begin{aligned}\mathcal{H}_{\rm eff}^{\rm NP} &= -\frac{\mathcal{G}_1}{\Lambda^2}[\overline{s}(1-\gamma^5)b]\,[\overline{b}(1+\gamma^5)b] \\ &\quad -\frac{\mathcal{G}_2}{\Lambda^2}[\overline{s}(1+\gamma^5)b]\,[\overline{b}(1-\gamma^5)b] + \mathrm{h.c.}\end{aligned}$$

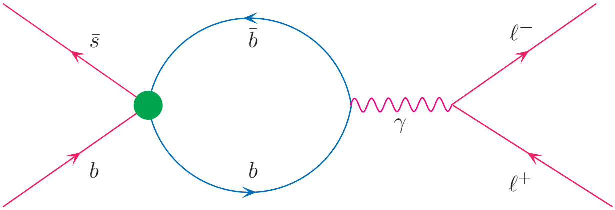
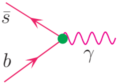


Figure:



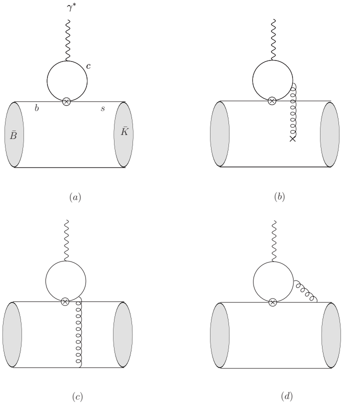
$$= -\sqrt{4\pi\alpha_{em}}e_b F(q^2)\bar{s}\left[\mathcal{G}_1\mathcal{R}_1^\mu + \mathcal{G}_2\mathcal{R}_2^\mu\right] b\, A_\mu$$

where $F(q^2) \sim \frac{q^2}{\Lambda^2}$. The q^2 is cancelled by the photon propagator to give ΔC_9.

- Since A_μ couples to electron and muons equally. This predicts same NP in electron and muon decays.

- To generate LUV we have to replace A_μ with a different boson which has LUV interactions.

Hadronic Uncertainties: 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 $R_K^{SM} = 1 \pm O(10^{-2})$ by 2.6σ, and is referred to as the R_K puzzle.

- This measurement is theoretically clean. Several same models for the P_5' anomaly can also explain R_K.

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

- $R_{K^{(*)}}$: Recently, LHCb Collaboration reported the measurement of the ratio $R_{K^*} \equiv \mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/\mathcal{B}(B^0 \to K^{*0}e^+e^-)$ in two different ranges of the dilepton invariant mass-squared q^2. The result was

$$R_{K^*}^{\rm expt} = \begin{cases} 0.660^{+0.110}_{-0.070}\,({\rm stat}) \pm 0.024\,({\rm syst}) & 0.045 \le q^2 \le 1.1~{\rm GeV}^2\,, \\ 0.685^{+0.113}_{-0.069}\,({\rm stat}) \pm 0.047\,({\rm syst}) & 1.1 \le q^2 \le 6.0~{\rm GeV}^2\,. \end{cases}$$

  These differ from the SM prediction of $R_{K^*}^{\rm SM}$ by 2.2-2.4σ (low q^2) or 2.4-2.5σ (medium q^2), and further strengthens the hint of lepton non-universality observed in R_K.
- Low q^2 dominated by photon pole which is not LUV. Hence measurement difficult to understand with heavy NP.

- Before $R_{K^{(*)}}$ there were several fits to NP for all the $b \to s\ell^+\ell^-$ observables (Descotes-Genon:2015uva, Alok:2017sui ...).
- 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.

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

Assuming the scale of NP is much larger than the weak scale, the semileptonic operators 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 for LH interactions:

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

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.

Models: Bhattacharya, Datta, Guevin, London, Watanabe

Models: Vector Bosons and Leptoqaurks.

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

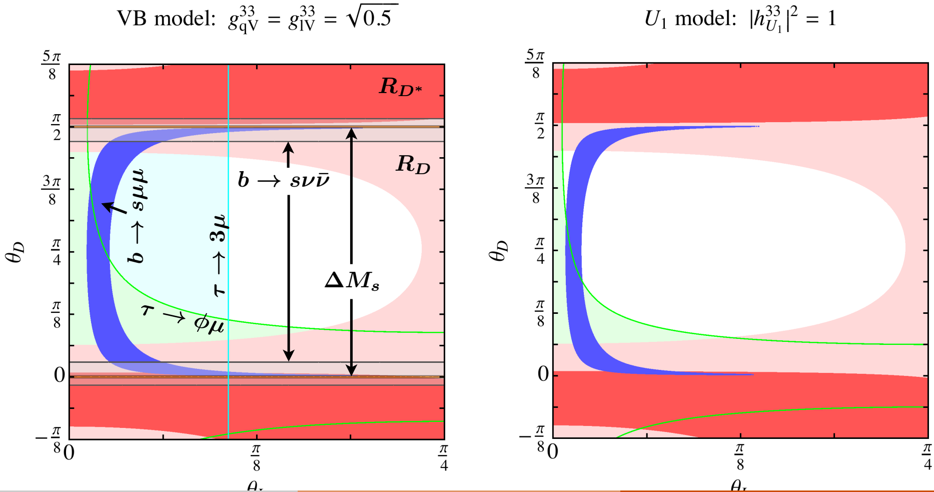
$$\mathcal{L}_V = g_{qV}^{33} \left(\overline{Q}'_{L3} \, \gamma^\mu \sigma^I \; Q'_{L3} \right) V_\mu^I + g_{\ell V}^{33} \left(\overline{L}'_{L3} \, \gamma^\mu \sigma^I \; L'_{L3} \right) V_\mu^I \, .$$

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

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

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.

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



$\tau \to 3\mu$ (Z' Model)

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.

Υ Modes(Leptoquarks)

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

$$
\begin{aligned}
VB & \qquad \mathcal{B}(\Upsilon(3S) \to \mu\tau) \simeq 3.0 \times 10^{-9} \ , \\
U_1 \quad : & \qquad \mathcal{B}(\Upsilon(3S) \to \mu\tau)|_{\rm max} = 8.0 \times 10^{-7} \ .
\end{aligned}
$$

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.

Recent Fits after $R_{K^{(*)}}$

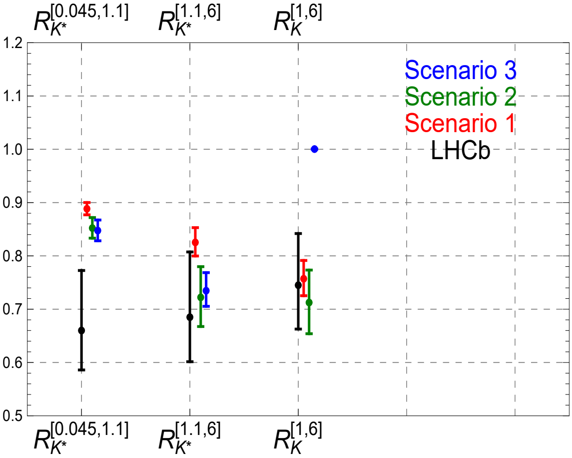
$$R_{K^*}^{\rm expt} = \begin{cases} 0.660^{+0.110}_{-0.070}\ ({\rm stat}) \pm 0.024\ ({\rm syst})\ , & 0.045 \le q^2 \le 1.1\ {\rm GeV}^2\ , \\ 0.685^{+0.113}_{-0.069}\ ({\rm stat}) \pm 0.047\ ({\rm syst})\ , & 1.1 \le q^2 \le 6.0\ {\rm GeV}^2\ . \end{cases}$$

arXiv:1704.07397 : Alok et.al.

Scenario	WC	pull
(I) $\Delta C_9^{\mu\mu}({\rm NP})$	-1.25 ± 0.19	5.9
(II) $\Delta C_9^{\mu\mu}({\rm NP}) = -\Delta C_{10}^{\mu\mu}({\rm NP})$	-0.68 ± 0.12	5.9
(III) $\Delta C_9^{\mu\mu}({\rm NP}) = -\Delta C_9^{'\mu\mu}({\rm NP})$	-1.11 ± 0.17	5.6

Table: Model-independent scenarios: best-fit values of the WCs (taken to be real), as well as the pull $= \sqrt{\chi^2_{SM} - \chi^2_{min}}$ for fit (B) (CP-conserving $b \to s\mu^+\mu^-$ observables + R_{K^*} and R_K). For each case there are 115 degrees of freedom.

Motivating light Z'



Question: Can we explain the R_K and $R_{K^{(*)}}$ measurements in all bins with light mediators. I will focus on $M < 200$ MeV mediators.

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

Relate R_K to $(g-2)_\mu$ and neutrino NSI.

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

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

where the form factor $F(q^2)$ can be constant or be a q^2 function (e.g. induced by four fermi operators).

In case $F(q^2) \neq 1$, it can be expanded as expanded as

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

when momentum transfer $q^2 \ll m_B^2$.

We assume Z' coupling to electrons is suppressed and $m_{Z'} < 2m_\mu$ and we can consider two cases:

Case A: Z' couples to neutrinos.

Case B : Z' does not couple to neutrinos.

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

Case A: The process $b \to s\nu_\alpha\bar{\nu}_\alpha$ decays is dominated by the two body $b \to sZ'$ decay with BR$[Z' \to \bar{\nu}\nu \sim 1]$.

There is a longitudinal polarization enhancement $\sim \frac{E_{Z'}}{m_{Z'}}$.

The coupling bsZ' is constrained by $B \to K\nu\bar{\nu}$ to be smaller than 10^{-9}.

$R_K \Rightarrow Z'$ coupling to muons to be $O(1)$ or larger which is in conflict with the $(g-2)_\mu$ measurement.

This constraint rules out $F(q^2) = 1$ and forces $a_{bs} \sim 0$, so that

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

Case B: Z' does not couple to neutrinos and so $F(q^2) = 1$ is allowed.

$$H_{bsZ'} = \bar{s}\gamma^\mu P_L b Z'_\mu,$$

$b \to s\ell^+\ell^-$

Case A: The Hamiltonian for $b \to s\ell\ell$ decays,

$$H_{bsll} = -\left[\frac{g^*}{q^2 - m_{Z'}^2}\right]\left[g_{bs}\frac{q^2}{m_B^2}\right]\bar{s}\gamma^\mu P_L b\bar{\ell}\gamma_\mu\ell\,.$$

Assume no NP with electrons. For $q^2 >> m_{Z'}^2$, the q^2 dependence cancels and a good fit to all observables except $R_{K^{(*)}}$ in the low q^2 bin be explained.

Case B: The Hamiltonian for $b \to s\ell\ell$ decays,

$$H_{bsll} = -\left[\frac{g^*}{q^2 - m_{Z'}^2}\right]\bar{s}\gamma^\mu P_L b\bar{\ell}\gamma_\mu\ell\,.$$

Assume no NP with electrons. The q^2 dependence does not cancel and a good fit to all observables cannot be obtained even for $R_{K^{(*)}}$ in the low q^2 bin.

Light Scalars and Z' coupling to electrons: Datta, Marfatia, Kumar, Liao

- Still need to explain low q^2, $R_{K^{(*)}}$ measurement.
- S coupling to muons does not work: R_K and $R_{K^{(*)}}$ increased from SM values.
- Z' couplings to muons do not work.
- We have to invoke NP coupling to electrons. $S(Z') \to e^+e^-$.
- We choose the mass of the new boson ~ 25 MeV to avoid branching ratio constraints. (All measurements have m_{ee} above 30 MeV.)

Electron couplings are constrained

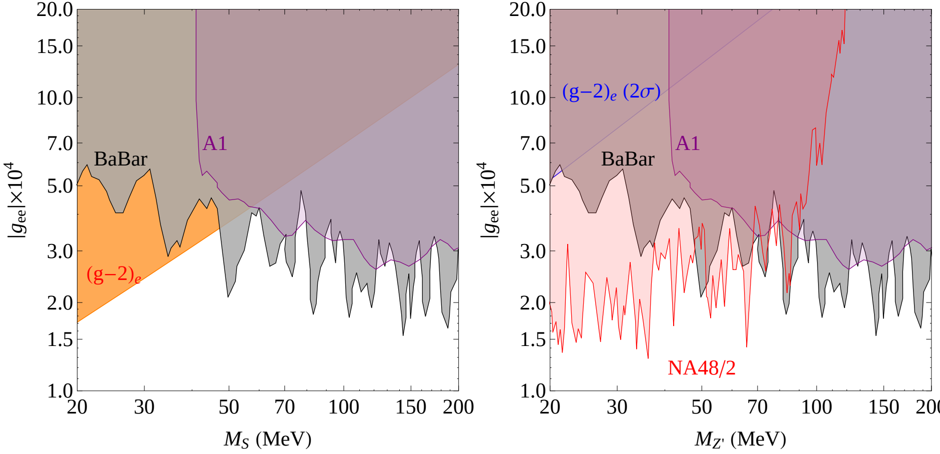


Figure:

fits

Case			$R_{K^*[0.045-1.1]}$	$R_{K^*[1.1-6.0]}$	$R_{K[1.0-6.0]}$	pull
Experimental results			0.66 ± 0.09	0.69 ± 0.10	0.75 ± 0.09	
Standard model predictions			0.93	0.99	1.0	
(i) Light scalar with electron coupling						
$F(q^2) \equiv 1,\ g^S_{ee} = 2.0 \times 10^{-4}$	$g^S_{bs} g^S_{ee} = (12.6 \pm 2.2) \times 10^{-9}$	$g^{S'}_{bs} g^S_{ee} = (4.0 \pm 1.6) \times 10^{-9}$	0.70	0.91	0.69	4.3
$a_{bs} \neq 0$	$g^S_{bs} g^S_{ee} = (-1.3 \pm 2.1) \times 10^{-9}$	$g^{S'}_{bs} g^S_{ee} = (-13.1 \pm 2.1) \times 10^{-9}$	0.58	0.85	0.75	4.7
$a_{bs} = 0$	$g^S_{bs} g^S_{ee} = (2.7 \pm 2.6) \times 10^{-8}$	$g^{S'}_{bs} g^S_{ee} = (-15.5 \pm 2.6) \times 10^{-8}$	0.89	0.65	0.75	4.4
(iii) Light vector with electron coupling						
$F(q^2) \equiv 1,\ g^{ee}_L = g^{ee}_R = 2.5 \times 10^{-4}$	$g_{bs} g_{ee} = (-0.6 \pm 1.0) \times 10^{-10}$	$g'_{bs} g_{ee} = (-0.4 \pm 1.1) \times 10^{-10}$	0.93	0.99	0.99	0.7
$a_{bs} \neq 0,\ g^{ee}_L = g^{ee}_R$	$g_{bs} g_{ee} = (-1.9 \pm 0.6) \times 10^{-9}$	$g'_{bs} g_{ee} = (-0.8 \pm 0.5) \times 10^{-9}$	0.62	0.92	0.74	4.5
$a_{bs} \neq 0,\ g'_{bs} = 0,\ g^{ee}_L \neq g^{ee}_R$	$g_{bs} g_{ee} = (-4.4 \pm 5.9) \times 10^{-10}$	$g_{bs} g'_{ee} = (7.5 \pm 3.3) \times 10^{-10}$	0.55	0.86	0.84	4.5
$a_{bs} \neq 0,\ g_{bs} = 0,\ g^{ee}_L \neq g^{ee}_R$	$g'_{bs} g_{ee} = (3.9 \pm 4.2) \times 10^{-10}$	$g'_{bs} g'_{ee} = (12.4 \pm 2.6) \times 10^{-10}$	0.58	0.98	0.81	4.0
$a_{bs} = 0,\ g^{ee}_L = g^{ee}_R$	$g_{bs} g_{ee} = (-3.9 \pm 1.0) \times 10^{-8}$	$g'_{bs} g_{ee} = (1.4 \pm 1.0) \times 10^{-8}$	0.78	0.60	0.75	4.8
$a_{bs} = 0,\ g'_{bs} = 0,\ g^{ee}_L \neq g^{ee}_R$	$g_{bs} g_{ee} = (-3.2 \pm 2.3) \times 10^{-8}$	$g_{bs} g'_{ee} = (0.4 \pm 1.4) \times 10^{-8}$	0.83	0.70	0.67	4.6
$a_{bs} = 0,\ g_{bs} = 0,\ g^{ee}_L \neq g^{ee}_R$	$g'_{bs} g_{ee} = (4.6 \pm 1.5) \times 10^{-8}$	$g'_{bs} g'_{ee} = (2.0 \pm 0.3) \times 10^{-8}$	0.80	0.58	0.77	4.7

Not all cases are consistent

Table: The experimental results for various $b \to s e^+ e^-$ observables, along with predictions for the SM and four new physics cases. The light mediator mass is 25 MeV, $F(q^2) \neq 1$ and $a_{bs} = 0$.

	$R_{K[0.045-1.0]}$	$\mathcal{B}(B \to K e^+ e^-)_{[1.0-6.0]}$	$\mathcal{B}(B \to X_s e^+ e^-)_{[1.0-6.0]}$	$B(B^0 \to K^{*0} e^+ e^-)_{[0.03^2-1]}$
Experimental results	-	$(1.56 \pm 0.18) \times 10^{-7}$	$(1.93 \pm 0.55) \times 10^{-6}$	$(3.1 \pm 0.9) \times 10^{-7}$
Standard model predictions	0.98	1.69×10^{-7}	1.74×10^{-6}	2.6×10^{-7}
Light scalar $g^S_{bs} g^S_{ee} = 2.7 \times 10^{-8}$, $g^{S'}_{bs} g^S_{ee} = -15.5 \times 10^{-8}$	0.93	2.5×10^{-7}	2.3×10^{-6}	2.6×10^{-7}
Light vector $g_{bs} g_{ee} = -3.9 \times 10^{-8}$, $g'_{bs} g_{ee} = 1.4 \times 10^{-8}$	0.73	2.4×10^{-7}	2.6×10^{-6}	2.8×10^{-7}
Light vector, $g'_{bs} = 0$ $g_{bs} g_{ee} = -3.2 \times 10^{-8}$, $g_{bs} g'_{ee} = 0.4 \times 10^{-8}$	0.66	2.7×10^{-7}	2.5×10^{-6}	2.7×10^{-7}
Light vector, $g_{bs} = 0$ $g'_{bs} g_{ee} = 4.6 \times 10^{-8}$, $g'_{bs} g'_{ee} = 2.0 \times 10^{-8}$	1.04	2.4×10^{-7}	2.5×10^{-6}	2.8×10^{-7}

R_K measurement in low q^2 bin can help probe various low mass mediator models.

Conclusions

- Several anomalies in B decays indicating lepton non-universal interactions.
- These 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.
- Light NP is highly constrained but some scenarios are viable.