Lepton Universality Violating Anomalies in B Decays

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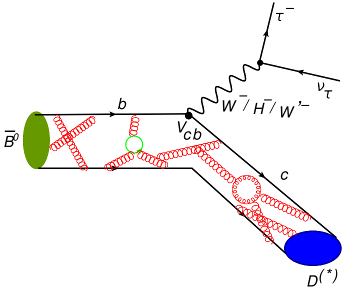
Outline of Talk

- 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: R_K, $R_{K^{(*)}}$ puzzles. BR of $b \to s\mu^+\mu^-$ modes are lower and also deviation in P_5' angular observable.
- These all indicate LUV New Physics.

Plan of the Talk

- If NP is present this can be probed in distributions and related decays.
- LUV can often lead to lepton flavor violation.
- I will consider simultaneous explanation of $R_{D^{(*)}}$ and R_K puzzles (1412.7164, 1609.09078, 1806.07403) and LFV tests .
- Finally, I will discuss light mediators explanation of the B anomalies.

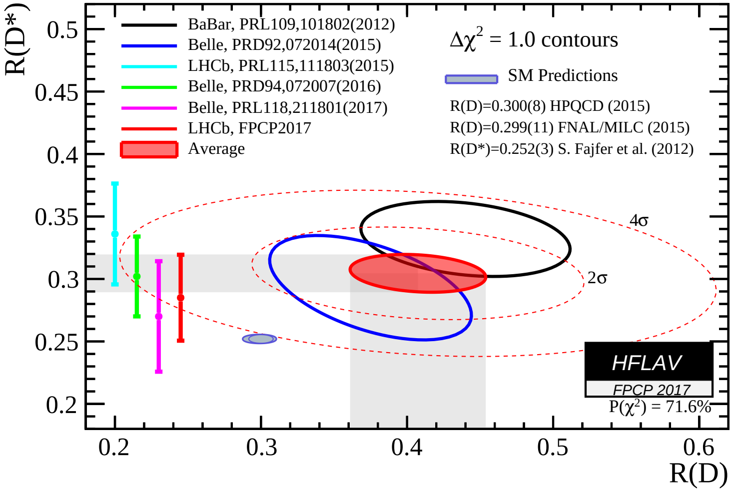
$R_{D^{(*)}}$ puzzle



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

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

R_D, R_{D^*}, HFAG



R(D*)
R(D)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.2
0.3
0.4
0.5
0.6
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, FPCP2017
Average
$\Delta\chi^2$ = 1.0 contours
SM Predictions
R(D)=0.300(8) HPQCD (2015)
R(D)=0.299(11) FNAL/MILC (2015)
R(D*)=0.252(3) S. Fajfer et al. (2012)
4σ
2σ
HFLAV
FPCP 2017
P(χ^2) = 71.6%

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

The average of $R(D)$ and $R(D^*)$ measurements evaluated by the Heavy-Flavor Averaging Group are

$$R(D)_{exp} = 0.407 \pm 0.039 \pm 0.024, \quad (1)$$
$$R(D^*)_{exp} = 0.304 \pm 0.013 \pm 0.007. \quad (2)$$

The combined analysis of $R(D)$ and $R(D^*)$, taking into account measurement correlations, finds that the deviation is at the level of 4.1σ from the SM prediction.

$$R(D)_{SM} = 0.298 \pm 0.003,$$
$$R(D^*)_{SM} = 0.255 \pm 0.004. \quad (3)$$

There are lattice QCD predictions for the ratio $R(D)_{SM}$ in the Standard Model that are in good agreement with one another,

$$R(D)_{SM} = 0.299 \pm 0.011 \quad \text{[FNAL/MILC]},$$
$$R(D)_{SM} = 0.300 \pm 0.008 \quad \text{[HPQCD]}.$$

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

At the m_b scale: $SU(3)_c \times U(1)_{em}$.

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

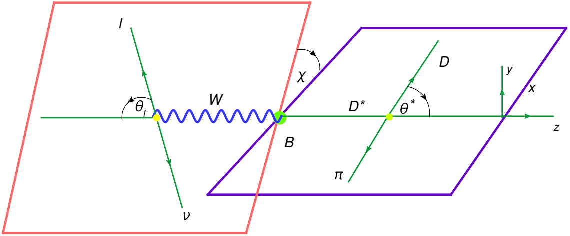
$$\mathcal{H}_{eff} = \frac{4 G_F V_{cb}}{\sqrt{2}} \Big[(1 + V_L) [\bar{c}\gamma_\mu P_L b] [\bar{l}\gamma^\mu P_L \nu_l] + V_R [\bar{c}\gamma^\mu P_R b] [\bar{l}\gamma_\mu P_L \nu_l]$$

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

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

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

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



Distributions have been measured by Belle for $B \to D^{(*)}\ell\nu_\ell$. We can then extract the Form Factors assuming no NP in these modes.

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

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

Decay Distribution described by Helicity Amplitudes

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

Distributions

- F_L (D^*) polarization. Distribution in θ^*.
- A_{FB} for both D and D^*. Distribution in θ_l.
- If we make the τ decay then we can measure the longitudinal tau polarization $P_\tau(D^{(*)})$.
- Finally we can look at CP violating terms in the angular distribution.

CPV Triple products

- There are triple products that appear in the angular distributions proportional to $\sin\chi$ (Datta and Duraisamy.)
- The triple product in the B rest frame: $\sim (\vec{n}_D \times \vec{n}_l).\vec{p}_{D^*} \sim \sin\chi$ with $\vec{n}_D \sim \vec{p}_D \times \vec{p}_\pi$ and $\vec{n}_l \sim \vec{p}_l \times \vec{p}_\nu$.
- These T.P. are proportional to $\mathcal{I}(H_i H_\perp^*)$. There are CPV. In the SM these terms are absent because all SM amplitudes have the same weak phase - V_{cb}.
- Since the p_τ momentum is not known we make the τ decay: $\tau \to V\nu_\tau$ and use the V momentum to construct the T.P. (Hagiwara, Nojiri, Sakaki).

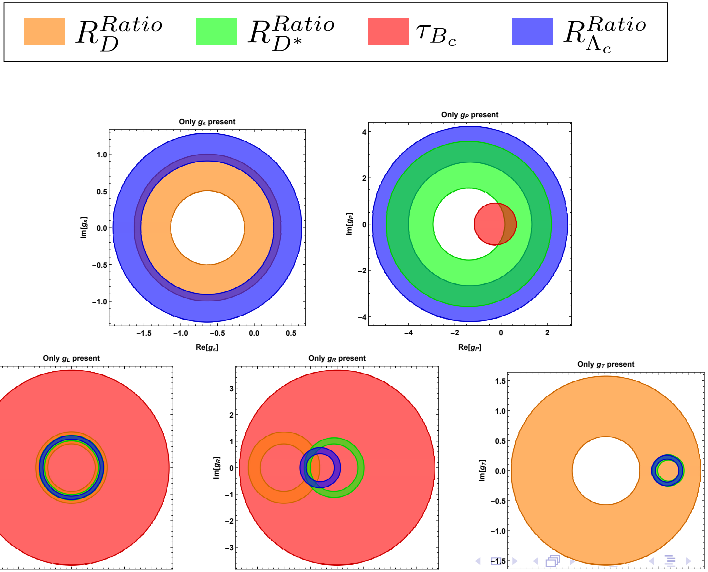
Other Decays

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). $\Gamma[B_c] > \Gamma[B_c \to \tau^- \bar{\nu}_\tau]$. g_P coupling is very constrained.
- $B_c \to J/\psi \tau^- \bar{\nu}_\tau$ LHCb measurement finds about a 2σ deviation from the SM.
- $b \to \tau \nu X$(LEP) (Saeed Kamali, AD).

- Measurements in $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$ can further constrain the NP parameter space. (Datta:2017aue, Shivashankara:2015cta).
- $\Lambda_b \to \Lambda_c$ form factors are calculated from lattice QCD (Datta:2017aue, Detmold:2015aaa)

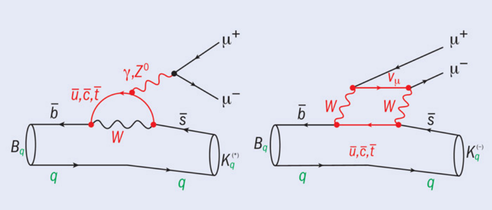
$R_{\Lambda_c}^{Ratio} = 1.3 \pm 3 \times 0.05$



Interesting Facts

- $$R(D)^{Ratio} = \frac{R(D)_{exp}}{R(D)_{SM}} = 1.36 \pm 0.15(1.30 \pm 0.17),$$
$$R(D^*)^{Ratio} = \frac{R(D^*)_{exp}}{R(D^*)_{SM}} = 1.19 \pm 0.06(1.25 \pm 0.08). \qquad (7)$$
- If NP is just $V - A$ then
$$R_D^{\rm ratio} \equiv \frac{R_D^{expt}}{R_D^{SM}} = |1 + V_L|^2 = R_{D^*}^{\rm ratio} \equiv \frac{R_{D^*}^{expt}}{R_{D^*}^{SM}} \ .$$
- If NP couples to RH particles only
$$R_D^{\rm ratio} \equiv \frac{R_D^{expt}}{R_D^{SM}} = (1 + |V_L|^2) = R_{D^*}^{\rm ratio} \equiv \frac{R_{D^*}^{expt}}{R_{D^*}^{SM}} \ .$$
W' models from $SU(2)_L \times SU(2)_V \times U(1)_X \to SU(2)_L \times U(1)_Y$ (1804.04135,1804.04642

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



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

R_K puzzle, Ratios of $b \to s\mu^+\mu^-$ and $b \to se^+e^-$. (Clean), 1708.02515

$$R_K \equiv \mathcal{B}(B^+ \to K^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+e^+e^-)$$

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

$1 \leq q^2 \leq 6.0\ \mathrm{GeV}^2$

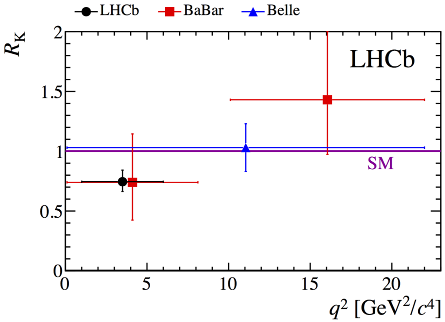
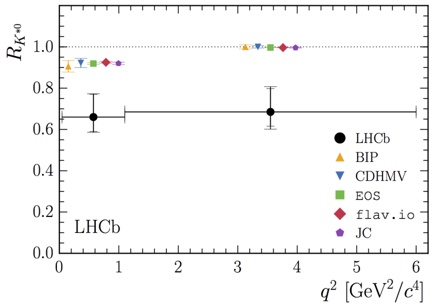


Figure: Comparison of the measurements of R_K from LHCb (black dots), BaBar (red squares) and Belle (blue triangles) with the SM expectation (purple line).



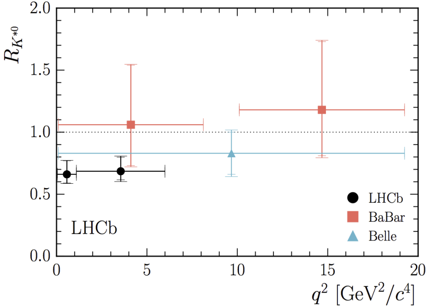


Figure: Comparison of the measurements of R_{K^*} from LHCb with (left) SM predictions and (right) BaBar and Belle.

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

R_K and R_{K^*} in the SM very close to 1 in the central bin and $R_{K^*} \sim 0.92$ in the low bin.

$R_{K^{(*)}}$ puzzle: Other Experiment

- Measurements from Belle finds difference in same q^2 bin as LHCb

$$Q_5 = P_5'(\mu\mu) - P_5'(ee)$$

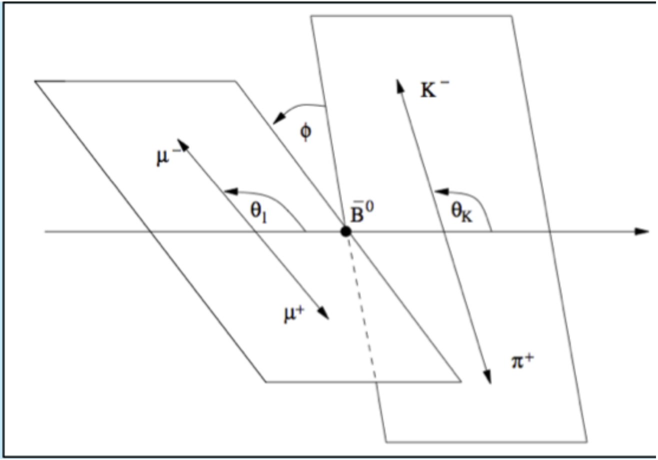
(1612.05014). Large errors.

- Low q^2 dominated by photon pole which is not LUV. Hence measurement difficult to understand with heavy NP.

Deviations in $b \to s\mu^+\mu^-$ Hadronic Uncertainty

- Anomalies appear in $B \to K^{(*)}\mu^+\mu^-$ (LHCb, Belle, Atlas, CMS) : Deviations are in branching ratios and in the angular observable like P_5'.
- BR are lower than the SM predictions.
- (LHCb) BR of $B_s^0 \to \phi\mu^+\mu^-$ are lower than SM predictions based on lattice QCD and QCD sum rules.
- Note all these are in $b \to s\mu^+\mu^-$ and the SM predictions are not free of hadronic uncertainties.

P_5' in $B \to K^*(K\pi)\mu^+\mu^-$



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

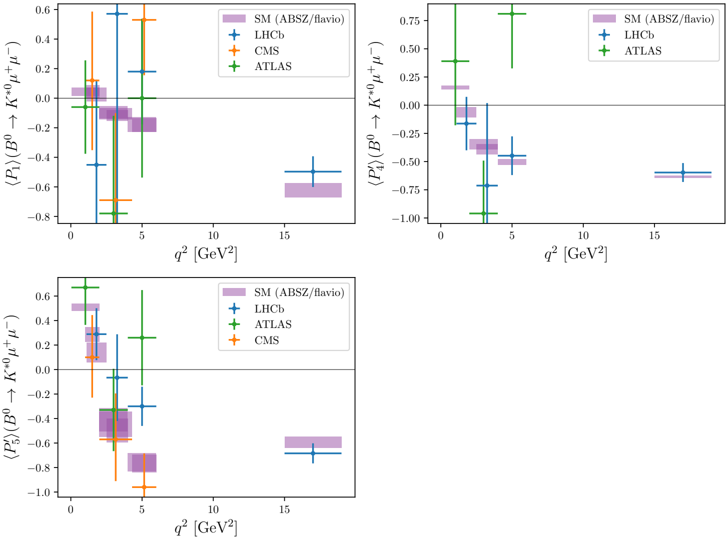
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\,\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}
= \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_k + F_{\mathrm{L}}\cos^2\theta_k
+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_k\cos 2\theta_l
-F_{\mathrm{L}}\cos^2\theta_k\cos 2\theta_l + S_3\sin^2\theta_k\sin^2\theta_l\cos 2\phi
+S_4\sin 2\theta_k\sin 2\theta_l\cos\phi + S_5\sin 2\theta_k\sin\theta_l\cos\phi
+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_k\cos\theta_l + S_7\sin 2\theta_k\sin\theta_l\sin\phi
+S_8\sin 2\theta_k\sin 2\theta_l\sin\phi + S_9\sin^2\theta_k\sin^2\theta_l\sin 2\phi\Big]. \tag{8}$$

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

$$\begin{aligned} P_1 &= \frac{2\,S_3}{(1-F_{\rm L})} = A_{\rm T}^{(2)}\,, \\ P_2 &= \frac{2}{3}\frac{A_{\rm FB}}{(1-F_{\rm L})}\,, \\ P_3 &= \frac{-S_9}{(1-F_{\rm L})}\,, \\ P'_{4,5,8} &= \frac{S_{4,5,8}}{\sqrt{F_{\rm L}(1-F_{\rm L})}}\,, \\ P'_6 &= \frac{S_7}{\sqrt{F_{\rm L}(1-F_{\rm L})}}\,. \end{aligned} \tag{9}$$

Just like $B \to D^{(*)}\tau\nu_\tau$ one can look at other observables like F_L, A_{FB} and CP violating co-efficients.

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]

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

Fits by many authors(1704.05435, 1704.05438, 1704.05444, 1705.05446, 1704.05447....) to all $b \to s\ell\ell$ observables: arXiv:1704.07397 : Alok et.al.

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

Here NP effects only the muons.

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), 1411.0565 pointed out in general
  LUV $\Rightarrow$ LFV.
  $$\frac{G}{\Lambda_{NP}^2}(\bar{b}'_L\gamma_\mu b'_L)(\bar{\tau}'_L\gamma^\mu\tau'_L) \; ,$$
  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.

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. (Bhattacharya, Datta, London, Shivshankara, 1412.7164) 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.

UV completion

- UV completions considered by many authors e.g. L. Calibbi, A. Crivellin and T. Ota, 1506.02661 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 $\mathcal{O}_2^{NP}$.

Models

- Note to simply explain $b \to s\ell^+\ell^-$ we can have Z' $(\mathbf{1}, \mathbf{1}, 0)$ from $U(1)$. One can consider both $(\mathbf{1}, \mathbf{3}, 0)$ and $(\mathbf{1}, \mathbf{1}, 0)$.
- Models with $U(2)_q \times U_l(2)$ flavor symmetry and breaking: See for example: Dario Buttazzo, Admir Greljo, Gino Isidori David Marzocca (Zurich U.) 1706.07808.
- Many of the general features can be understood in a simple analysis.
- In models other processes get affected and so specific models are more constrained.

Models: Bhattacharya, Datta, Guevin, London, Watanabe, 1609.09078

Models: Vector Bosons and Leptoqaurks.

Transform to the mass basis:

$$u'_L = U u_L \ , \quad d'_L = D d_L \ , \quad \ell'_L = L \ell_L \ , \quad \nu'_L = L \nu_L \ ,$$

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:

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

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

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

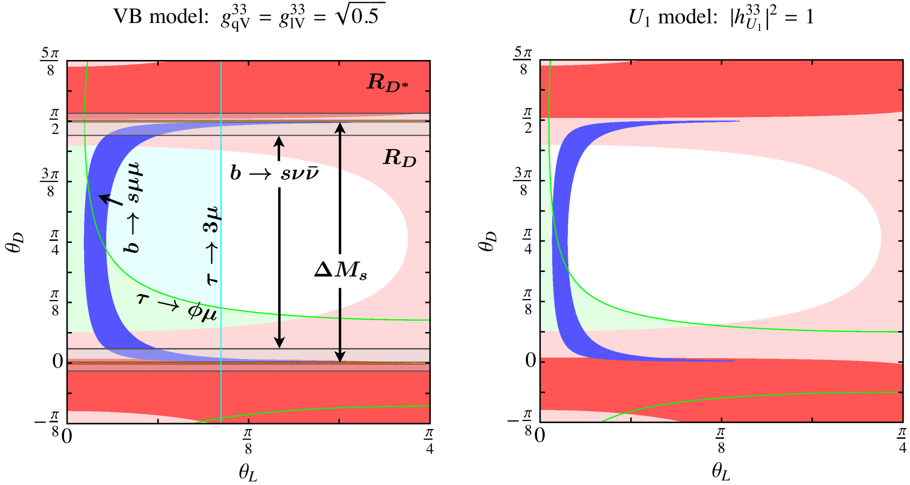
$$\mathcal{L}_V = g_{qV}^{33} \left(\overline{Q}'_{L3} \, \gamma^\mu \sigma^I \; Q'_{L3} \right) V_\mu^I + g_{\ell V}^{33} \left(\overline{L}'_{L3} \, \gamma^\mu \sigma^I \; L'_{L3} \right) V_\mu^I \, .$$

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

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

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)

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

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

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

  Belle II should be able to measure $\mathcal{B}(\Upsilon(3S) \to \mu\tau)$ down to $\sim 10^{-7}$.

- Even though we do not find observable effects in $b \to s\tau\tau$ or $b \to s\tau\mu$ others have have found larger effects(See for e.g. 1703.09226).

Collider Search: 1706.07808

High-p_T searches are concerned, particularly stringent bounds are set by $pp \to \tau\bar{\tau} + X$

$$\Delta\mathcal{L}_{bb\tau\tau} = -\frac{1}{\Lambda_0^2}\ \left(\bar{b}_L\gamma_\mu b_L\right)\left(\bar{\tau}_L\gamma_\mu\tau_L\right)\ , \qquad \Lambda_0^2 = \frac{v^2}{G_1 + G_2}\ . \tag{10}$$

The present bounds on the EFT scale Λ_0 were derived recasting different ATLAS searches for $\tau\bar{\tau}$ resonances, and read $\Lambda_0 > 0.62\,\mathrm{TeV}$. Newer fits: $\Lambda_0 \approx 1.2$ TeV, which is well within the experimental limit.

Lepton flavor violating decays: $gg \to \tau\mu$ (1802.06082, 1802.09822) or $gg \to \bar{t}t\tau\mu$ (1412.7164).

$$\Delta\mathcal{L}_{tt\tau\mu} = -\frac{1}{\Lambda_0^2}\ \left(\bar{t}_L\gamma_\mu t_L\right)\left(\bar{\tau}_L\gamma_\mu\mu_L\right) \tag{11}$$

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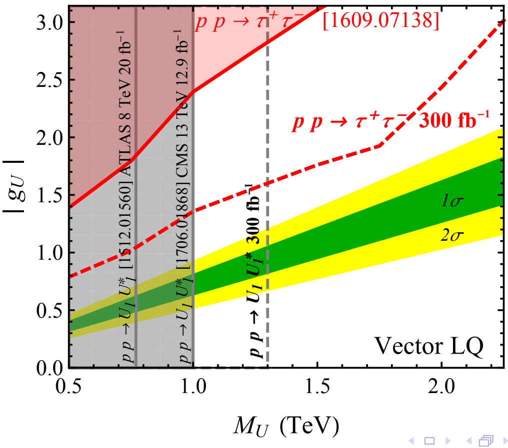
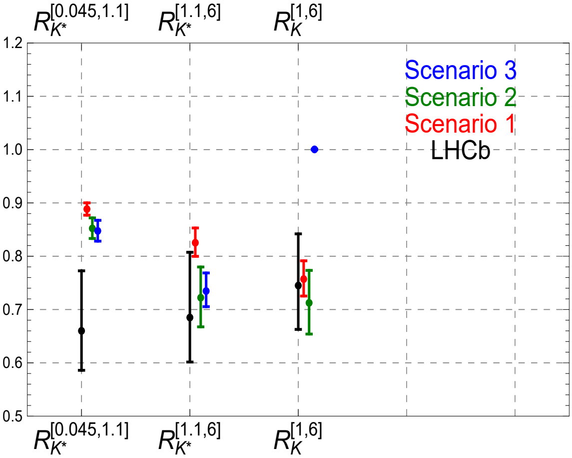
Z' $(\mathbf{1}, \mathbf{3}, 0)$ is strongly constrained(ruled out) unless width is large. Z' $(\mathbf{1}, \mathbf{1}, 0)$ explaining only R_K is fine: $M_{Z'} \sim 30$ TeV.



Motivating light Z'



Question: Can we explain the low q^2 $R_{K^{(*)}}$ measurement with light mediators.

Scope of the Model

Try to explain R_K and $R_{K^{(*)}}$ in "all" bins.
(1705.08423, 1704.07397, 1702.01099). Harder- very constraining.

Try to explain $R_{K^{(*)}}$ in "only" the low q^2 bin. "Easier"(1711.07494).

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

Focus on high q^2 bins only, $q^2 > 1\text{GeV}^2$.

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

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

Will consider tree level and loop induced couplings.

We assume Z' coupling to electrons is suppressed and $m_{Z'} < 2m_\mu$. There are negative searches bump in $X \to \mu^+\mu^-$ in $B \to KX$ and then $X \to \mu^+\mu^-$

$b \to sZ'$, Constant Form Factor $F(q^2) = 1$, Tree Level

- For R_K we have off-shell contribution : $B \to KZ'^*(\to \mu^+\mu^-)$.

$$g_{bs}g_{\mu\mu} \sim 10^{-9}; \quad M_{Z'} \sim 100 MeV.$$

- There is contribution to B_s mixing which strongly constrains

$$g_{bs} \sim 10^{-7} - 10^{-8}$$

.

- $SU(2)_L$ invariance $\Rightarrow$ coupling to $(\nu, \ell)_L^T$. If Z' couples to neutrinos then $B \to K\nu\bar{\nu}$ is a 2-body decay.

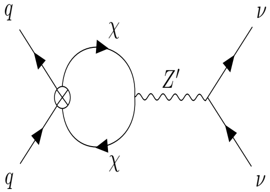
$$BR[B \to K\nu\bar{\nu}] = BR[B \to KZ'] \times BR[Z' \to \nu\bar{\nu}].$$

$B \to K^{(*)}\nu\bar{\nu}$ constrain $\Rightarrow g_{bs} \sim 10^{-9}$.

- $g_{\mu\mu} \sim 1$ (too large) $\Rightarrow$ problem with $(g-2)_\mu$.

Loop induced

- To generate LUV we have (Z'_μ) which has LUV interactions and couples to quarks via loop.



$$\mathcal{L} = \frac{g}{\Lambda^2}\overline{q_{iL}}Y_{ij}\gamma^\mu q_{jL}\ \bar{\chi}_L\gamma_\mu\chi + g_\chi\bar{\chi}\gamma_\rho\chi Z'^\rho + g_\ell\bar{\ell}\left[A_L\gamma_\rho(1-\gamma_5) + A_R\gamma_\rho(1+\gamma_5)\right]\ell Z'^\rho\,,$$

χ loop produces a $\bar{q}_i q_j Z'$ coupling that goes a $\frac{q^2}{\Lambda^2}$. We take $m_\chi \sim m_b$.

$F(q^2) \neq 1$, Loop Induced

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

for $q^2 << m_B^2$.

- B_s mixing constrains $F(q^2 = m_B^2)$.
- $B \rightarrow K\nu\bar{\nu} \Rightarrow g_{bs} \sim 10^{-5} \Rightarrow g_{\mu\mu} \sim 10^{-4}$ and $(g-2)_\mu$ can be explained.
  Note,
  $$\frac{q^2}{q^2 - m_{Z'}^2} \rightarrow 1,$$
  when $q^2 >> m_{Z'}^2$.
  So this low mass NP appears as ΔC_9 from heavy NP. So "all" observables, R_K and angular measurements are explained except $R_{K^{(*)}}$ in low q^2 bin.

Summary: Explain R_K, $R_{K^{(*)}}$ in all bins

- Tree level bsZ' for MeV Z' ruled out.
- Loop Induced FCNC coupling of Z' is allowed with $FF \sim q^2$ for $q^2 << m_B^2$. But still need to explain low q^2, $R_{K^{(*)}}$ measurement. Other observables can be explained.
- Scalar S coupling to muons does not work : R_K and $R_{K^{(*)}}$ increased from SM values. No interference with the SM.
- Scalar and vector coupling to electrons can work for all bins with $FF \sim q^2$ for $q^2 << m_B^2$(1705.08423).

Explaining only the low q^2 bin 1711.07494

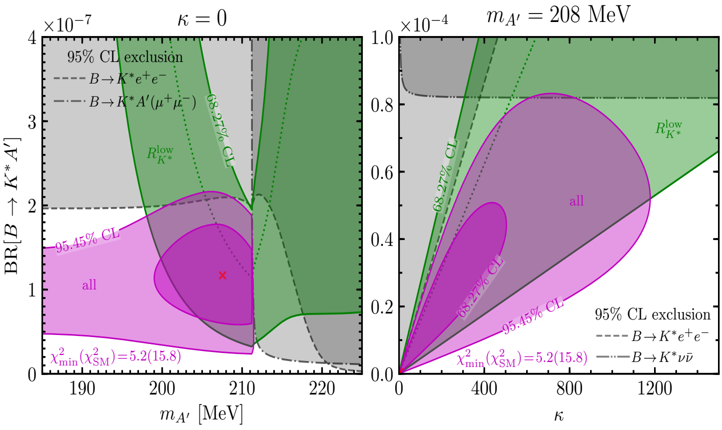
In this case, assume a resonance near the low q^2 bin and then

$$BR[B \to K^* \ell\ell] \;=\; BR[B \to K^* \ell\ell]_{SM} + BR[B \to K^* X] \times BR[X \to \ell\ell]$$

X does not need to have LUV couplings. For instance if $m_X < 2m_\mu$ then only $B \to K^* e^+ e^-$ is affected. So in fact X can have lepton universal coupling and can be a dark photon for example.

A dark photon with mass just bellow the $2m_\mu$ threshold can explain the low q^2 $R_{K^{(*)}}$ measurement.

Dark photon



$\kappa = 0$
$\times 10^{-7}$
95% CL exclusion
$B \to K^* e^+ e^-$
$B \to K^* A'(\mu^+\mu^-)$
68.27% CL
$R_{K^*}^{\rm low}$
95.45% CL
all
$\chi^2_{\rm min}(\chi^2_{\rm SM}) = 5.2(15.8)$
$\mathrm{BR}[B \to K^* A']$
0
1
2
3
4
190
200
210
220
$m_{A'}$ [MeV]
$m_{A'} = 208$ MeV
$\times 10^{-4}$
0.0
0.2
0.4
0.6
0.8
1.0
0
400
800
1200
κ
$R_{K^*}^{\rm low}$
68.27% CL
all
95.45% CL
$\chi^2_{\rm min}(\chi^2_{\rm SM}) = 5.2(15.8)$
95% CL exclusion
$B \to K^* e^+ e^-$
$B \to K^* \nu \bar{\nu}$

Explaining only the low q^2 bin Feng, Datta, Kamali

Familon model:

$$\mathcal{L}_{Q'Q'} = \frac{g_Q}{F_Q} \bar{Q}'_\alpha \gamma^\mu P_L T^a_{\alpha\beta} Q'_\beta \partial_\mu f^a \ ,$$

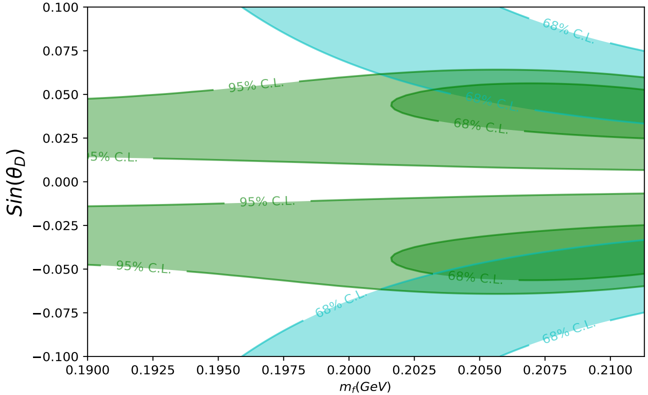
where $Q'_L = (u_L, d_L)^T$ are the left-handed quark doublets. The quarks are in the gauge basis and are indicated by primes. For the lepton couplings we write,

$$\mathcal{L}_{L'L'} = \frac{g_L}{F_L} \bar{L'}_\alpha \gamma^\mu P_L S^a_{\alpha\beta} L'_\beta \partial_\mu f^a \ ,$$

where $L'_L = (\nu_L, \ell_L)^T$ are the left-handed quark doublets. The leptons are in the gauge basis and are indicated by primes. Note we do not assume F_L and F_Q are the same.

Familon

$U(1)$ Family Symmetry. Coupling $\sim$ mass. Fit prefers $F_Q >> F_L$. Have to fix $(g-2)_\mu$- contribution is too large and opposite sign.



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.