Joint Explanation of Flavor Anomalies

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July 18-20, 2019

Flasy 2019

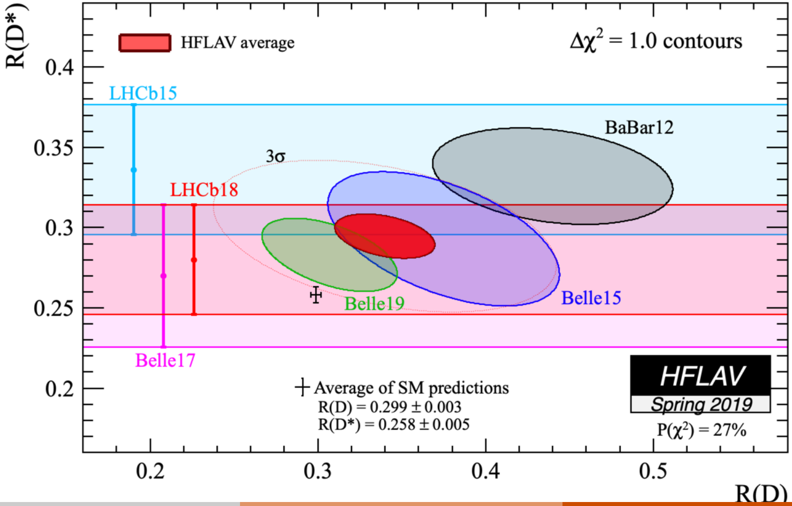
Several New Measurements- Many anomalies.

- Measurement of CP violation in the up-sector (NP ?).
- Semileptonic B anomalies- $R_{D^{(*)}}$ and R_K puzzles.
- Nonleptonic B decay anomaly: $B \to \pi K$ puzzle.
- In K Decays: $Re[\frac{\epsilon'}{\epsilon}]$.
- $(g-2)_\mu$ of the muon, $(g-2)_e$ of the electron(?).
- CPV in $\tau^- \to K^- \pi^0 \nu_\tau$.
- LSND, MiniBoone, Reactor... Anomalies.

Are the Anomalies related?

- Combined explanations of the CC and NC semileptonic B anomalies.
- $(g-2)_\mu$ and the semileptonic B anomalies: Constant FCNC coupling.
- $(g-2)_\mu$ and the semileptonic B anomalies: Loop induced couplings: FCNC coupling $\sim q^2$.
- Loop induced couplings and effects in neutrino scattering (arXiv:1808.0261 JHEP).
- Combined framework for the semileptonic and nonleptonic anomalies and effect on neutrino mass and mixing.

R_D, R_{D^*}, HFAG



R(D*)
0.4
0.35
0.3
0.25
0.2
HFLAV average
$\Delta\chi^2 = 1.0$ contours
LHCb15
BaBar12
3σ
LHCb18
Belle19
Belle15
Belle17
Average of SM predictions
R(D) = 0.299 ± 0.003
R(D*) = 0.258 ± 0.005
HFLAV
Spring 2019
P(χ²) = 27%
0.2
0.3
0.4
0.5
R(D)

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

$$R(D)_{exp} = 0.340 \pm 0.027 \pm 0.013,$$
$$R(D^*)_{exp} = 0.295 \pm 0.011 \pm 0.008.$$

According to 1904.09311

$$R(D)_{SM} = 0.300^{+0.005}_{-0.004}$$
$$R(D^*)_{SM} = 0.251^{+0.004}_{-0.003}$$

There are also measurements of q^2 distribution, $F_L^{D^*}$, τ polarization.

Model independent NP analysis

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

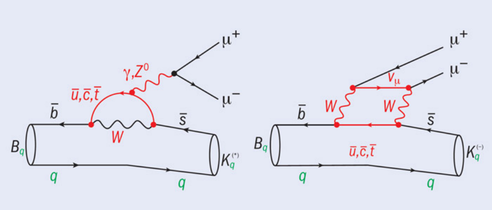
- Effective Hamiltonian for $b \to c l^- \bar{\nu}_l$ with Non-SM couplings. The NP has to be LUV.

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

The NP can be probed via distributions and other related decays. Recent fit 1904.09311 find a good fit with LH interactions.

Other options viable: 1211.0348, 1704.06659,1711.09525, 1804.04135,1804.04642, 1804.04753, 1810.06597, 1811.04496...

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



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

Hadronic Uncertainties: Charm Loop effects: Ciuchini et.al. 1512.07157

$b \to s\mu^+\mu^-$ can also receive corrections from non-leptonic operators

$$M = \left\langle K^*\mu^+\mu^- \right| \bar{s}b\bar{q}q \left| B \right\rangle$$

$\bar{q}q \to \gamma^* \to \mu^+\mu^-$. There can also be resonant contributions $\bar{q}q \to J/\psi \to \mu^+\mu^-$.

This long distance dominated contribution cannot be calculated from first principle. There are factorization theorem for small q^2 in leading order in m_{heavy}. But sub-leading corrections are not known.

$$M = \bar{s}\gamma_\mu P_L b \left[\frac{H(q^2)}{q^2}\right] \bar{\mu}\gamma^\mu \mu$$

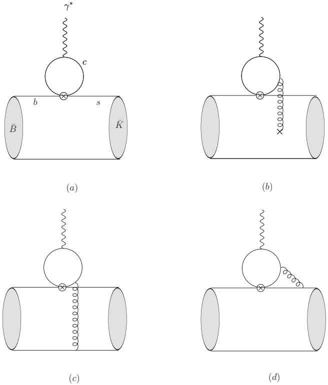
$$H(q^2) = a + b\frac{q^2}{m_B^2} \ldots..$$

$H(q^2) \sim q^2$ and you reproduce ΔC_9 from pure SM hadronic effect.

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

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

The SM prediction of $R_K^{\mathrm{SM}} = 1 \pm 0.01$

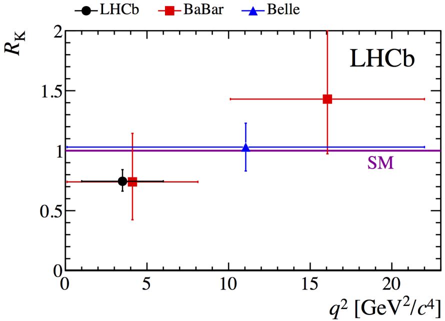


These effects can fake a ΔC_9 but this is lepton universal and so cannot explain R_K and R_{K^*} if $q^2 > 4m_\mu^2$.

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

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

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



Recently, LHCb announced new R_K.

First, the Run I data was reanalyzed using a new reconstruction selection method. The new result is

$$R_{K,\mathrm{Run\ 1}}^{\mathrm{new}} = 0.717^{+0.083}_{-0.071}\ (\mathrm{stat})^{+0.017}_{-0.016}\ (\mathrm{syst})\ .$$

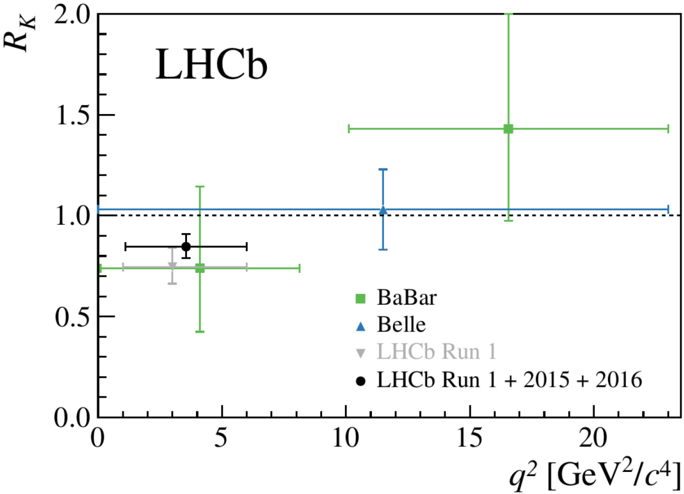
Second, the Run 2 data was analyzed:

$$R_{K,\mathrm{Run\ 2}} = 0.928^{+0.089}_{-0.076}\ (\mathrm{stat}) \pm^{+0.020}_{-0.017}\ (\mathrm{syst})\ .$$

Combining the Run 1 and Run 2 results, the LHCb measurement of R_K is

$$R_K = 0.846^{+0.060}_{-0.054}\ (\mathrm{stat})^{+0.016}_{-0.014}\ (\mathrm{syst})\ .$$

This is closer to the SM prediction, though the discrepancy is still $\sim 2.5\sigma$ due to the smaller errors.



[Th.Humair,talkatMoriond2019]

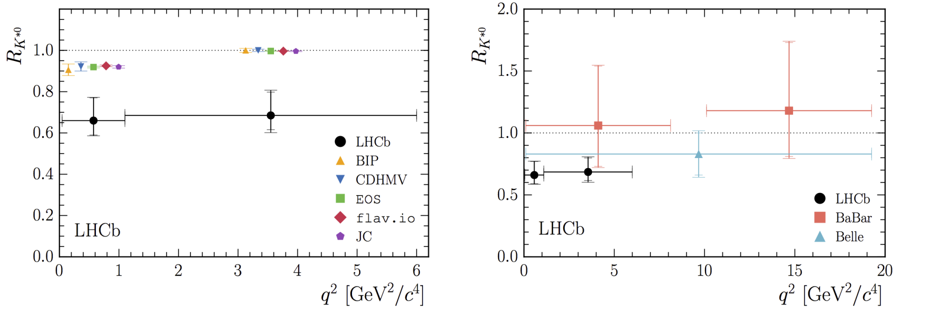


Figure: Comparison of the measurements of R_{K^*} from LHCb with (left) SM predictions and (right) BaBar and Belle.

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

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.

Model Independent

The $b \to s\mu^+\mu^-$ transitions are defined via an effective Hamiltonian with vector and axial vector operators:

$$
\begin{aligned}
H_{\rm eff} &= -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \sum_{a=9,10} (C_a O_a + C'_a O'_a) \ , \\
O_{9(10)} &= [\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu(\gamma_5)\mu] \ ,
\end{aligned}
$$

where the V_{ij} are elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix and the primed operators are obtained by replacing L with R.

The Wilson coefficients (WCs) include both the SM and NP contributions: $C_a^{(\prime)} = C_{a,{\rm SM}} + C_{a,{\rm NP}}^{(\prime)}$

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

Fits by many authors- recent (1902.04900, 1903.09617, 1903.10086, 1903.10434....) to all $b \to s\ell\ell$ observables: arXiv:1903.10086

Scenario	WC	R_K	$R_{K^*}^{cen}$	$R_{K^*}^{low}$	P_5'	pull
(I) $C_{9,\mathrm{NP}}^{\mu\mu}$	-1.10 ± 0.16	0.78	0.84	0.89	-0.50	5.6
(II) $C_{9,\mathrm{NP}}^{\mu\mu} = -C_{10,\mathrm{NP}}^{\mu\mu}$	-0.53 ± 0.08	0.76	0.76	0.86	-0.70	5.3

Table: Best-fit values of the WCs (taken to be real), the predictions for R_K, $R_{K^*}^{cen}$, $R_{K^*}^{low}$ and P_5', evaluated at these best-fit values, and the pull $= \sqrt{\chi^2_{\mathrm{SM}} - \chi^2_{\mathrm{SM+NP}}}$ for the global fit including all $b \to s\mu^+\mu^-$ and $R_{K^{(*)}}$ observables. For each case there are 115 degrees of freedom.

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.

Interesting trend

Scenario	Data Set	WC
(I) $C_{9,\mathrm{NP}}^{\mu\mu}$	$R_{K^{(*)}}$	-0.82 ± 0.28
	$b \to s\mu^+\mu^-$	-1.17 ± 0.18
(II) $C_{9,\mathrm{NP}}^{\mu\mu} = -C_{10,\mathrm{NP}}^{\mu\mu}$	$R_{K^{(*)}}$	-0.38 ± 0.11
	$b \to s\mu^+\mu^-$	-0.62 ± 0.14

Table: Best-fit values of the WCs (taken to be real) for separate fits including the $b \to s\mu^+\mu^-$ or $R_{K^{(*)}}$ observables.

- Before new results there was overlap of NP in $R_{K^{(*)}}$ and $b \to s\mu^+\mu^-$.
- Internal tension in $R_{K^{(*)}}$ and $b \to s\mu^+\mu^-$ NP could indicate NP in $b \to se^+e^-$.
- NP in $b \to se^+e^-$ also indicated in low q^2 R_{K^*} measurement.

Model Building: Neubert: 2018 SUSY

Model building

- Several (but not all) models aim at explaining all anomalies, sometimes along with $(g\text{-}2)_\mu$ (optimistic 😊)

  [Bhattacharya, Datta, London, Shivashankara 2014; Alonso, Grinstein, Martin Camalich 2015; Greljo, Isidori, Marzocca 2015; Calibbi, Crivellin, Ota 2015; Bauer, MN 2015; Fajfer, Kosnik 2915; Barbieri, Isidori 2015; Das, Hati, Kumar, Mahajan 2016; Boucenna, Celis, Fuentes-Martin, Vicente, Virto 2016; Becirevic, Kosnik, Sumensari, Zukanovich Funchal 2016; Becirevic, Fajfer, Kosnic, Sumensari 2016; Hiller, Loose, Schoenwald 2016; Bhattacharya, Datta, Guevin, London, Watanabe 2016; Buttazzo, Greljo, Isidori, Marzocca 2016; Barbieri, Murphy, Senia 2016; Bordone, Isidori, Trifinopoulos 2017; Crivellin, Müller, Ota 2017; Megias, Quiros, Salas 2017; Cai, Gargalionis, Schmidt, Volkas 2017; …]

- R_D and R_{D^*} require tree-level NP near TeV scale
- Rare decays $b \to s\ell^+\ell^-$ (R_K, R_{K^*}, P_5', …) require suppressed NP contributions
- If common origin: suppression either dynamically or by means of a symmetry

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. (Bhattacharya, Datta, London, Shivshankara, 1412.7164) considered two possibilities for LH interactions:

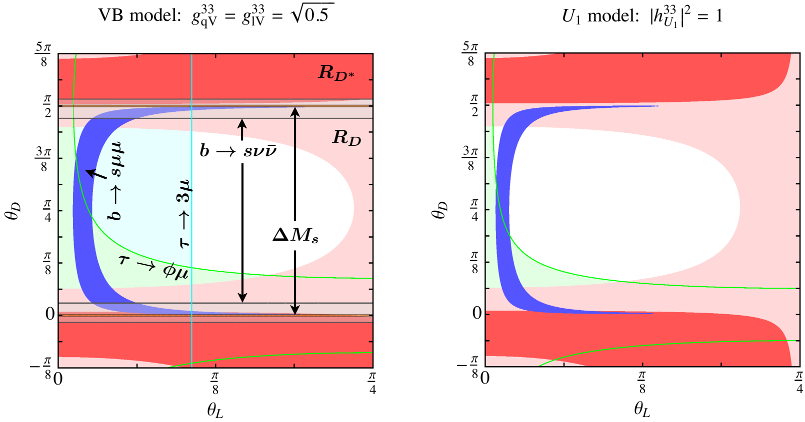
$$
\begin{aligned}
\mathcal{O}_1^{NP} &= \frac{G_1}{\Lambda_{NP}^2}(\bar{Q}'_L\gamma_\mu Q'_L)(\bar{L}'_L\gamma^\mu L'_L) \, , \\
\mathcal{O}_2^{NP} &= \frac{G_2}{\Lambda_{NP}^2}(\bar{Q}'_L\gamma_\mu\sigma^I Q'_L)(\bar{L}'_L\gamma^\mu\sigma^I L'_L) \\
&= \frac{G_2}{\Lambda_{NP}^2}\left[2(\bar{Q}'^i_L\gamma_\mu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

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: allowed parameter space: 1609.09078, 1806.07403



Z' models highly constrained. U_1 LQ is the favored model.

Predictions(Leptoquarks)

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

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

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

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

- Large observable effects in $b \to s\tau^+\tau^-$ ($B \to K^{(*)}\tau^+\tau^-$, $B_s \to \tau^+\tau^-$) or $b \to s\tau\mu$ and possibly LFUV in $B \to \pi\ell\bar{\nu}_\ell$ Decays.

Collider Search: 1706.07808

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

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

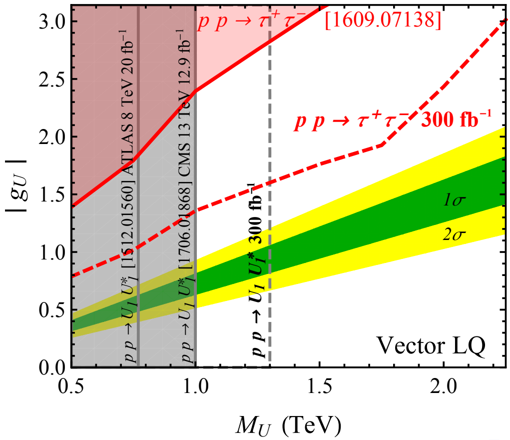
The present bounds on the EFT scale Λ_0 were derived recasting different ATLAS searches for $\tau\bar{\tau}$ resonances, and read $\Lambda_0 > 0.62\,\mathrm{TeV}$. Newer fits: $\Lambda_0 \approx 1.2$ TeV, which is well within the experimental limit.

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

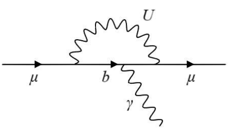
$$\Delta\mathcal{L}_{tt\tau\mu} = -\frac{1}{\Lambda_0^2}\left(\bar{t}_L\gamma_\mu t_L\right)\left(\bar{\tau}_L\gamma_\mu\mu_L\right) \tag{2}$$

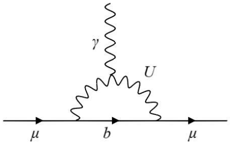
Collider Search: 1706.07808

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.



$(g-2)_\mu$ and B anomalies





$$\Delta(g-2)^U_\mu = -\frac{N^c (h^U_{i\mu})^2}{16\pi^2}\left(\frac{4m_\mu^2}{3m_U^2}Q_b - \frac{5m_\mu^2}{3m_U^2}Q_U\right), \tag{3}$$

where $N^c = 3$ is the number of colors, $i = d, s, b$ and $Q_b = -\frac{1}{3}$ and $Q_U = -\frac{2}{3}$ are the electric charges of the bottom quark and the U leptoquark. Putting in the numbers for the muon mass, we find,

$$\Delta(g-2)^U_\mu = -1.4 \times 10^{-10}(h^U_{i\mu})^2\left(\frac{\text{TeV}}{m_U}\right)^2, \tag{4}$$

Add NP for $(g-2)_\mu$

- We try to solve. $(g-2)_\mu$ with a light mediator with mass around 50-200 MeV with mass below the two muon threshold.
- Such light mediators are also motivated by the neutrino anomalies.
- Light mediators have also been motivated by the low q^2 bin of $R_{K^{(*)}}$ with couplings to electrons.

$(g-2)_\mu$ and B anomalies: General Comments

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

The most general form of the $bsZ'(S)$ vertex with vector type coupling is

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

Tree level or Loop induced: $F(q^2) \sim$ constant.

Loop Induced:$F(q^2) \sim q^2$: example conserved vector current.

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

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

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

We assume $Z'(S)$ 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 $F(q^2) = 1$

- 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 $(g-2)_\mu \Rightarrow g_{\mu\mu} \sim 10^{-4}$.

What do we learn

If a light particle solves $(g-2)_\mu$ then the B anomalies (neutral current) cannot be explained by a constant FCNC $b \to s$ vertex

You need additional new physics to explain the B anomalies. Maybe these new particles have some interactions with the light states.

$F(q^2) \neq 1$ 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 $F(q^2 = m_B^2)$.
- $B \to K\nu\bar{\nu} \Rightarrow g_{bs} \sim 10^{-5} \Rightarrow g_{\mu\mu} \sim 10^{-4}$ and $(g-2)_\mu$ can be explained.
  Note,

$$\frac{q^2}{q^2 - m_{Z'}^2} \to 1,$$

  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.

$(g-2)_\mu$ and B anomalies: Model: Dark Higgs

- A light scalar with coupling $\frac{m_\mu}{v} \sim 4 \times 10^{-4}$ solves the $(g-2)_\mu$.
- Dark photon ruled out as solution to the $(g-2)_\mu$.
- Dark Higgs: Singlet field S.

$$V_{\text{portal}} = (\alpha_1 S + \alpha_2 S^2) H^\dagger H$$

- We assume S does not develop a v.e.v.
- S mixes with Higgs and couples to SM fermions $\sim g_* \frac{m}{v}$

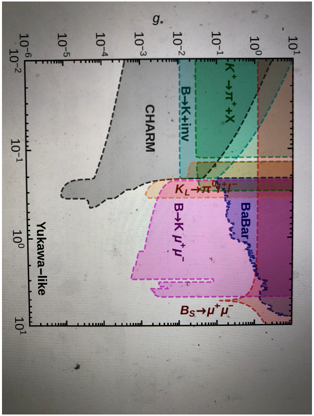
$(g-2)_\mu$ and B anomalies: Model: Dark Higgs

- S is produced through the penguin $B \to KS, D \to \pi S$ and $K \to \pi S$
- For m_S below muon threshold S decays to electron-positron pair and diphoton with decay to electron-positron pair dominant for m_S between 50 to 200 MeV.
- Constraints come from $B_s \to \mu^+\mu^-$, $B \to K + invisible$, $K \to \pi + invisible$ and beam dump experiments.

$$c\tau_s \approx 50m \left(\frac{0.02}{g_*}\right)^2 \frac{50MeV}{m_S}$$

$(g-2)_\mu$ and B anomalies: Dark Higgs

$g_* \sim 10^{-4}$ cannot explain $(g-2)_\mu$: Require $g_{\mu\mu} \sim g_* \frac{m_\mu}{v} \sim \frac{m_\mu}{v} \sim 4 \times 10^{-4}$



Suppress the penguin and make S short lived to avoid beam dump constraints.

$(g-2)_\mu$ and B anomalies: Dark Higgs in 2HDMII

Our model is an extension of the Type II 2HDM.

We extend this by adding a singlet scalar ϕ, which couples to the Higgs doublets through the portal interactions

$$
\begin{aligned}
V_{\rm portal} &= A\,(H_u^\dagger H_d + H_d^\dagger H_u)\phi \\
&+ \left[\lambda_u H_u^\dagger H_u + \lambda_d H_d^\dagger H_d + \lambda_{ud}(H_u^\dagger H_d + H_d^\dagger H_u)\right]\phi^2 \ .
\end{aligned}
$$

H_u and H_d get vevs, but ϕ doesn't.

After electroweak symmetry breaking, then, the trilinear scalar couplings mix the new scalar with the Higgs bosons of the 2HDM, and the quartic scalar couplings contribute to new Higgs boson decays $h \to \phi\phi$ and to the mass of the ϕ.

Physical Basis

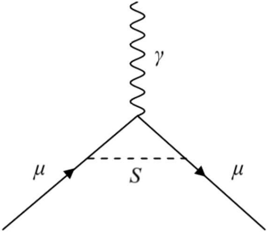
In the physical basis $\phi \to S$.

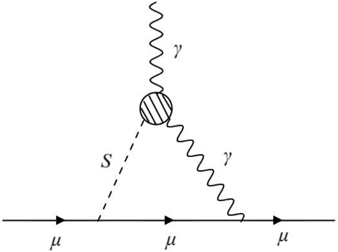
$$\mathcal{L}_S = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \sin\theta \tan\beta \sum_{f=d,l} \frac{m_f}{v}\bar{f}fS - \sin\theta' \cot\beta \sum_{f=u} \frac{m_f}{v}\bar{f}fS - \frac{1}{4}\kappa S F_{\mu\nu}F^{\mu\nu},$$

$$\sin\theta \simeq -\frac{vA}{m_H^2}\,, \quad \sin\theta' \simeq -\frac{2vA}{m_h^2}\left(1 - \frac{m_h^2}{2m_H^2}\right).$$

The last term of is an $S\gamma\gamma$ coupling parametrized by the mass scale m_κ. This coupling is generically induced by heavy states, such as leptoquarks, as will be discussed next.

$(g-2)_\mu$ in the Model





- If coupling to photon is absent then $(g-2)_\mu$ requires

$$\sin\theta\tan\beta \sim 1$$

.

- We will require $m_H \leq$ 1TeV which from 2HDMII fits could allow $\tan\beta \leq 40$.

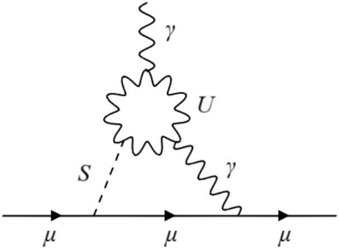
$(g-2)_\mu$ in the Model

- Assume $m_H \leq 1$TeV then we can choose $\sin\theta \sim 0.005$ which corresponds to $\sin\theta' \sim 0.6$.
- Note $\sin\theta'$ controls the FCNC penguin terms and cannot be made too large.
- This implies $\tan\beta \sim 200$ which is ruled out for $m_H \leq 1$TeV from 2HDMII fits.
- So additional contribution to $(g-2)_\mu$ from the diphoton term is required.

B anomalies and the $S\gamma\gamma$ term

- To solve the B anomalies we introduce the LQ U_1.
- The $S\gamma\gamma$ is generated through the LQ triangle loop.

$$\mathcal{L}_U = -\frac{1}{4} F^U_{\mu\nu} F^{U\mu\nu} - m_U^2 U_\mu U^\mu - \left[h^U_{ij} \left(\bar{Q}_{iL} \gamma^\mu L_{jL} \right) U_\mu + \text{H.c.} \right] - g m_U S U_\mu U^\mu \, . \quad (5)$$



The U_1 LQ coupling to S has to be too large to generate the required $S\gamma\gamma$ for $(g-2)_\mu$.

$S\gamma\gamma$

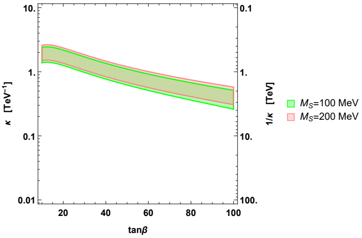
Introduce additional LQ field.

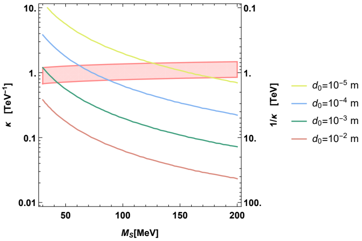
$$\begin{aligned}\mathcal{L}_{V_i} &= -\frac{1}{4}F^{V_i}_{\mu\nu}F^{V_i\mu\nu} - m^2_{V_i}V_{i\mu}V^{\mu}_{i} - \left[h^V_{jk}\left(\bar{Q}_{jR}\gamma^{\mu}L_{kR}\right)V_{i\mu} + \text{H.c.}\right] \\ &- g_{V_i}m_{V_i}SV_{i\mu}V^{\mu}_{i} \ ,\end{aligned}$$

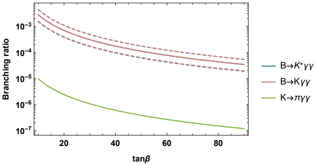
where for simplicity we add only leptoquarks with SM quantum numbers $(3, 1, \frac{5}{3})$.

- Models: LQ maybe bound states of some confining dynamics. See e.g. (1710.02140......)- So expect large multiplicities of states.
- $(g-2)_{\mu}$ requires S decays dominantly to di photons and tiny BR to $e^{+}e^{-}$.

$(g-2)_\mu$ and B anomalies





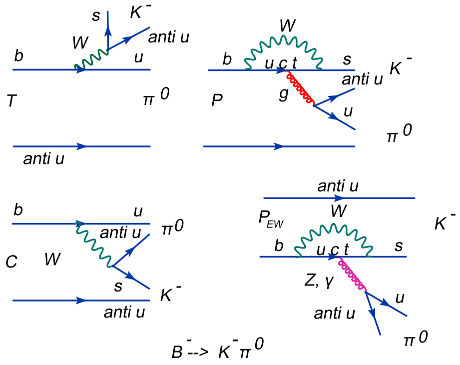


$B \to K^{(*)}\gamma\gamma \sim 10^{-4}$. Some of the decay will look like $B \to K^{(*)}\gamma$ for small $m_S \sim 50-100$ MeV.

$B \to K\pi$- SM

In the SM the amplitudes for the four decays can be related by isospin.

The four decays can be represented by the following amplitudes:



$$\frac{|T|}{|P|} = \frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*}\frac{c_1}{c_t} \sim 0.2 \quad \frac{|C|}{|P|} \sim \frac{1}{N_c}\frac{|T|}{|P|} \sim 0.04 \quad \frac{|P_{EW}|}{|P|} \sim 0.14$$

$B \to \pi K$ puzzle

We begin by reviewing the $B \to \pi K$ puzzle. Including only the leading diagrams the $B \to \pi K$ amplitudes become

$$\begin{aligned} A^{+0} &= -P'_{tc} \ , \\ \sqrt{2}A^{0+} &= -T' e^{i\gamma} + P'_{tc} - P'_{EW} \ , \\ A^{-+} &= -T' e^{i\gamma} + P'_{tc} \ , \\ \sqrt{2}A^{00} &= -P'_{tc} - P'_{EW} \ . \end{aligned}$$

In A^{0+}, P'_{EW} and T' have the same strong phase ($P'_{EW} \propto T'$, while P'_{EW} and P'_{tc} have the same weak phase ($= 0$), so that P'_{EW} does not contribute to the direct CP asymmetry. This means that we expect $A_{CP}(B^+ \to \pi^0 K^+) = A_{CP}(B^0_d \to \pi^- K^+)$.

Not only are $A_{CP}(B^+ \to \pi^0 K^+)$ and $A_{CP}(B_d^0 \to \pi^- K^+)$ not equal, they are of opposite sign! Experimentally, we have $(\Delta A_{CP})_{\rm exp} = (12.2 \pm 2.2)\%$. This differs from 0 by 5.5σ. This is the naive $B \to \pi K$ puzzle.

Mode	$BR[10^{-6}]$	A_{CP}	S_{CP}
$B^+ \to \pi^+ K^0$	23.79 ± 0.75	-0.017 ± 0.016	
$B^+ \to \pi^0 K^+$	12.94 ± 0.52	0.040 ± 0.021	
$B_d^0 \to \pi^- K^+$	19.57 ± 0.53	-0.082 ± 0.006	
$B_d^0 \to \pi^0 K^0$	9.93 ± 0.49	-0.01 ± 0.10	0.57 ± 0.17

Table: Branching ratios, direct CP asymmetries A_{CP}, and mixing-induced CP asymmetry S_{CP} (if applicable) for the four $B \to \pi K$ decay modes. The data are taken from HFAG.

Semileptonic and NonLeptonic

LQ solve the SL anomalies.

For the nonleptonic two kinds of NP are possible: Z' and Diquarks (1709.07142).

$$b \to sZ' \to b \to s\bar{q}q \quad b \to \bar{q}D(D \to sq).$$

Consider a model with with triplet LQ $(3, 3, -1/3)$ and a color sextet $(6, 1, -2/3)$ Diquark.

With the particle content discussed above, the most general interaction lagrangian is given as

$$\mathcal{L}_{int} = -Y_l^{ij}\, \overline{L_i^c}\, i\, \sigma_2\, Q_j^{\alpha}\, S_{3L}^{\alpha *} - Y_d^{ij}\, \overline{d_{iR}^{\alpha c}}\, d_{jR}^{\beta}\, S_D^{\alpha\beta *} + \mu\, S_{3L}^{\alpha *}\, S_{3L}^{\beta *}\, S_D^{\alpha\beta} + (h.c.),$$

Colored Zee Babu Model

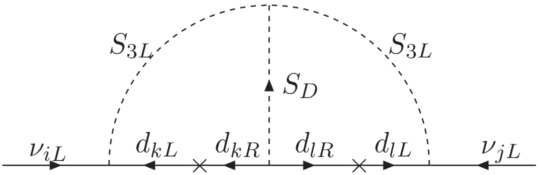


Figure: The two loop neutrino mass generated by $(3, 3, -1/3)$ leptoquark and $(6, 1, -2/3)$ diquark.

$$M_\nu^{ij} = 24\,\mu\, Y_l^{ik} [m_d^k\, Y_d^{kl} I^{kl} m_d^l]\, Y_l^{lj}. \tag{6}$$

A consistent framework to address the SL, NL B anomalies and neutrino masses is possible: 1905.04046

Diquarks produce Mixing

Neutral Meson Mixing

$$\left[\mathcal{O}_{mix} = \frac{Y_d^{*ij} Y_d^{kl}}{m_S^2} \bar{\psi}^k{}_R \gamma^\mu \psi^i{}_R \, \bar{\psi}^l{}_R \gamma_\mu \psi^j{}_R\right]$$

The 90 % C.L bounds on the corresponding Wilson coefficients is then given as:

$$\begin{array}{lccc} \mathbf{K}^\circ - \overline{\mathbf{K}^\circ} & \left|\frac{Y_d^{*11} Y_d^{22}}{4\sqrt{2} G_F m_S^2}\right| & < & 2.9 \times 10^{-8} \\ \mathbf{B}^\circ_\mathbf{d} - \overline{\mathbf{B}^\circ_\mathbf{d}} & \left|\frac{Y_d^{*11} Y_d^{33}}{4\sqrt{2} G_F m_S^2}\right| & < & 7.0 \times 10^{-7} \\ \mathbf{B}^\circ_\mathbf{s} - \overline{\mathbf{B}^\circ_\mathbf{s}} & \left|\frac{Y_d^{*22} Y_d^{33}}{4\sqrt{2} G_F m_S^2}\right| & < & 3.3 \times 10^{-5} \end{array}$$

To be consistent with collider searches(diject searches) $m_S \simeq 5 \to 20$ TeV.

Nonleptonic Decays

The diquarks of neutrino mass generation can contribute to nonleptonic $b \to \bar{d}_i d_j d_k$ and in particular $B \to \pi K$ decays (Giudice:2011ak) and the measurement of these decays put constraints on the model.

$$\mathcal{H}^d_{NP} = X^d \, \bar{d}_{\alpha,k}\gamma_\mu(1+\gamma^5)b_\alpha \, \bar{d}_{\beta,j}\gamma^\mu(1+\gamma^5)d_{\beta,i},$$

where the superscript d in X^d equals 6 or $\overline{3}$ corresponding to the color sextet or the anti-triplet diquark. The greek subscripts represent color and the latin subscripts the flavor. We have

$$X^d = -\frac{Y^d_{i3} Y^{*d}_{jk}}{4m_S^2},$$

where the Yukawa Y are symmetric for the sextet diquark and antisymmetric for the ant-triplet diquark and we have assumed the same masses for the diquarks.

$B \to \pi K$

- Since diquark couples to down type quarks we can have nonleptonic decays of B and K mesons.
- Since diagonal terms are suppressed many decays are highly suppressed.

For $b \to s\bar{d}d$($b \to \bar{d}sd$ and $b \to \bar{d}ds$) transitions we have the following Hamiltonian

$$\begin{aligned}\mathcal{H}^d_{NP} &= X^d\, \bar{s}_\alpha \gamma_\mu (1+\gamma^5) b_\alpha\, \bar{d}_\beta \gamma^\mu (1+\gamma^5) d_\beta \\ &+ X^d_C\, \bar{s}_\alpha \gamma_\mu (1+\gamma^5) b_\beta\, \bar{d}_\beta \gamma^\mu (1+\gamma^5) d_\alpha,\end{aligned}$$

with

$$\begin{aligned}X^d &= -\frac{Y^d_{13} Y^{*d}_{12}}{4m_S^2}, \\ X^d_C &= -\frac{Y^d_{13} Y^{*d}_{21}}{4m_S^2}.\end{aligned}$$

The only other unsuppressed transition is $b \to s\bar{s}d$($b \to \bar{s}sd$ and $b \to \bar{s}ds$) which has the effective Hamiltonian,

$$\begin{aligned}\mathcal{H}_{NP}^{d} &= X^{d}\,\bar{s}_{\alpha}\gamma_{\mu}(1+\gamma^{5})b_{\alpha}\,\bar{d}_{\beta}\gamma^{\mu}(1+\gamma^{5})s_{\beta}\\ &+ X_{C}^{d}\,\bar{s}_{\alpha}\gamma_{\mu}(1+\gamma^{5})b_{\beta}\,\bar{d}_{\beta}\gamma^{\mu}(1+\gamma^{5})s_{\alpha},\end{aligned}$$

with

$$\begin{aligned}X^{d} &= -\frac{Y_{23}^{d}\,Y_{12}^{*d}}{4m_{S}^{2}},\\ X_{C}^{d} &= -\frac{Y_{23}^{d}\,Y_{21}^{*d}}{4m_{S}^{2}}.\end{aligned}$$

In this case at the meson level we can have the decays $B \to \phi\pi$ and the annhilation decays $B \to \phi\phi$. These decays are highly suppressed in the SM and the observance of these decays could signal the presence of diquarks.

Constraints from neutrino masses makes these decays highly suppressed.

Conclusions

- Measurements B decays indicating lepton non-universal interactions.
- Combined explanations:These anomalies may arise from the same New Physics.
- Combined Explanations: $(g-2)_\mu$ and the S.L. B anomalies
- If true then new states like new gauge bosons, leptoquarks could be discoved.
- Combined Explanation of nonleptonic and semileptonic anomalies have interesting implications for neutrino physics.