Light Mediators in B 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 $b \to s\ell^+\ell^-(l = \mu, e)$ 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

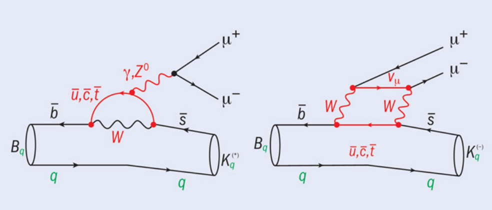
- Focus on the neutral current anomalies: $b \to s\mu^+\mu^-$ decays and R_K and $R_{K^{(*)}}$ puzzles.

- NP explanation in terms of heavy mediators. Can light mediators explain the anomalies?

- Low q^2 measurement of $R_{K^{(*)}}$ difficult to understand with heavy new physics $\sim$ TeV.

- Will consider light new physics with MeV scale mediators .

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



$$H_{\rm eff}(b \to s\ell\bar{\ell}) = -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left[C_9 \, (\bar{s}_L \gamma^\mu b_L)\,(\bar{\ell}\gamma_\mu \ell) + C_{10} \, (\bar{s}_L \gamma^\mu b_L)\,(\bar{\ell}\gamma_\mu \gamma^5 \ell)\right] ,$$

$$H_{\rm eff}(b \to s\nu\bar{\nu}) = -\frac{\alpha G_F}{\sqrt{2}\pi} V_{tb} V_{ts}^* \, C_L \, (\bar{s}_L \gamma^\mu b_L)\,(\bar{\nu}\gamma_\mu (1-\gamma^5)\nu) ,$$

$$H_{\rm eff}(b \to s\gamma^*) = C_7 \, \frac{e}{16\pi^2} \left[\bar{s}\sigma_{\mu\nu}(m_s P_L + m_b P_R) b\right] F^{\mu\nu}$$

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

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

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

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

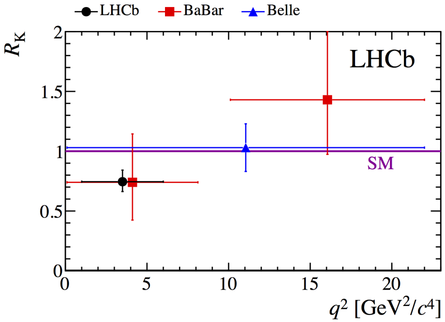


Figure: Comparison of the measurements of R_K from LHCb (black dots), BaBar (red squares) and Belle (blue triangles) with the SM expectation (purple line).

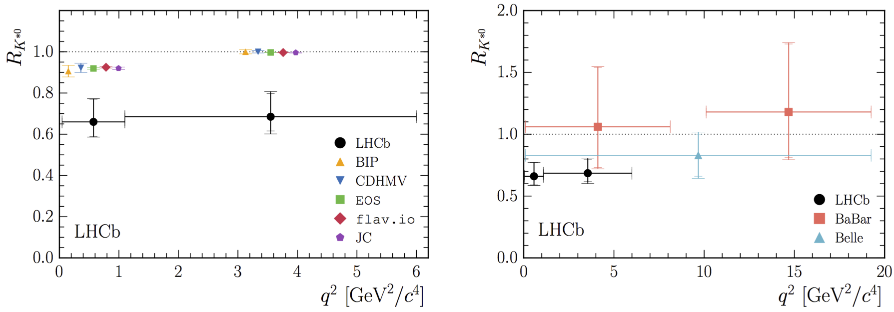


Figure: Comparison of the measurements of R_{K^*} from LHCb with (left) SM predictions and (right) BaBar and Belle.

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

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 $R_{K^{(*)}}$ measurement dominated by photon pole which is not LUV. Hence measurement difficult to understand with heavy NP.

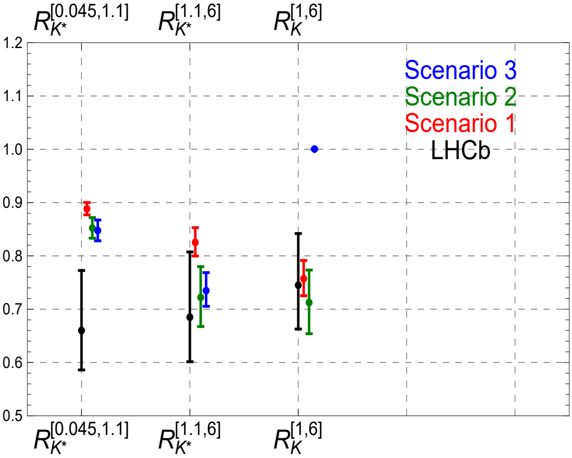
Recent Fits after $R_{K^{(*)}}$

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.

Motivating light Z'- not the only motivation.



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.

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).

Possibilities: Dark photon, dark Higgs, ALP e.t.c.

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

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

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

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

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

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 $F(q^2) = 1$

- Only off-shell contribution : $B \to KZ'^{*}(\to \mu^+\mu^-)$. From R_K

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

- There is contribution to B_s mixing which strongly constrains

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

. $D_{\mu\nu} \sim \left[g_{\mu\nu} - \frac{q_\mu q_\nu}{m_X^2}\right]$.

- $SU(2)_L$ invariance $\Rightarrow$ coupling to $(\nu, \ell)_L$. If Z' couples to neutrinos then

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

There is a longitudinal polarization enhancement $\sim \frac{E_{Z'}}{m_{Z'}} \Rightarrow g_{bs} \sim 10^{-9}$.

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

$F(q^2) \neq 1$

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

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

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

- B_s mixing constrains $F(q^2 = m_B^2)$.
- $B \to K\nu\bar{\nu} \Rightarrow g_{bs} \sim 10^{-5} \Rightarrow g_{\mu\mu} \sim 10^{-4}$.

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

where $q^2 >> m_{Z'}^2$. So this low mass NP appears as ΔC_9 from heavy NP. So "all" observables, R_K and angular measurements are explained. But $R_{K^{(*)}}$ in low q^2 bin cannot be explained.

Origin of the Form Factor: Charm Loop effects: Ciuchini et.al. 1512.07157

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

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

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

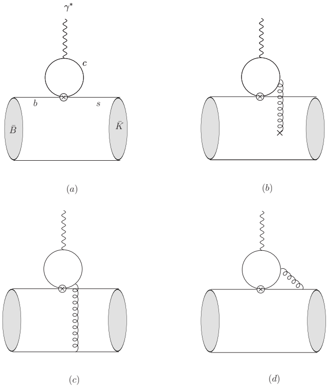
This long distance dominated contribution cannot be calculated from first principle. There are factorization theorem for small q^2 in leading order in m_{heavy}. But sub-leading corrections are not known.

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

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

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

Hadronic Uncertainties: Charm Loop effects: eprint: 1006.4945



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

Four quark operators, Datta, Duraisamy, Ghosh, 1310.1937

Some NP 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

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

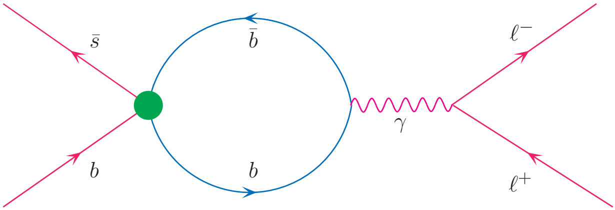
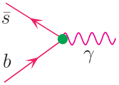


Figure:

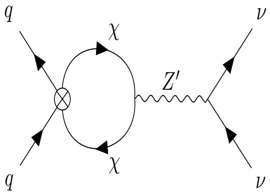


$$= -\sqrt{4\pi\alpha_{em}} e_b F(q^2) \bar{s} \left[\mathcal{G}_1 \mathcal{R}_1^{\mu} + \mathcal{G}_2 \mathcal{R}_2^{\mu} \right] b \, A_{\mu}$$

where $F(q^2) \sim \frac{q^2}{m_\Lambda^2}$. 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 for $q^2 > 4m_\mu^2$.

- To generate LUV we have to replace A_μ with a different boson (Z'_μ) which has LUV interactions.



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

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

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

- Tree level bsZ' for MeV Z' ruled out.

- Form Factor 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).

Light Scalars and Z' coupling to electrons and muons: Datta, Marfatia, Jacky 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 $\sim$ 25 MeV to avoid branching ratio constraints. (All measurements have m_{ee} above 30 MeV.)

Electron couplings are constrained

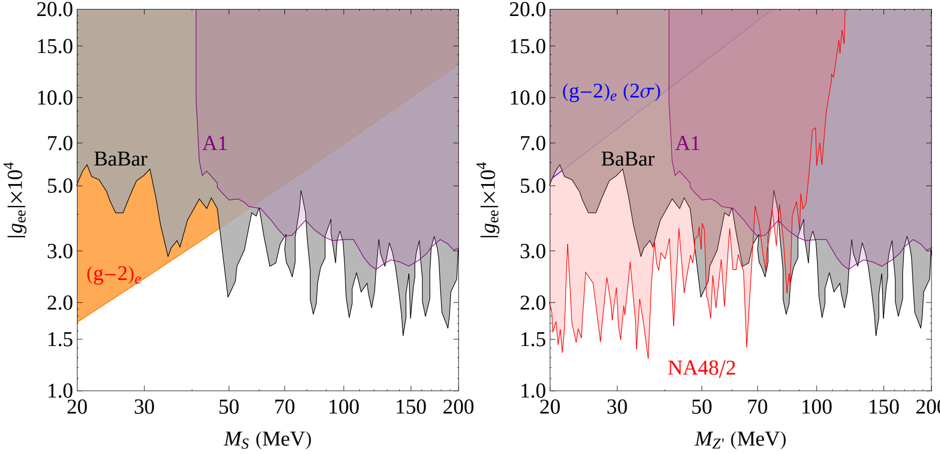


Figure:

Two Body Problem.

- Main problem is from two body decays: $B \to KX$ and $X \to e^+e^-$.
- The B width is calculated with uncertainty of about 10%.
- Requiring $\Gamma[B \to KX] \leq 1\ \%\ \Gamma_B$ forces g_{bs} to be $10^{-8} - 10^{-9}$.
- $g_{ee} \leq 10^{-3}$ and so $g_{bs} g_{ee} \sim 10^{-11} - 10^{-12}$ and so too small for $R_{K^{(*)}}$.
- Forced into sbX Form factor to go as $F(q^2) \sim q^2$.

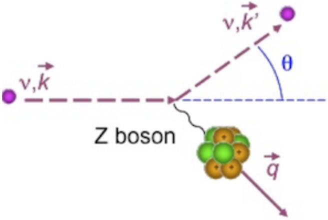
Table: The experimental results for various $b \to se^+e^-$ observables, along with predictions for the SM and four new physics cases. The light mediator mass is 25 MeV, $F(q^2) \neq 1$ and $a_{bs} = 0$.

	$R_{K[0.045-1.0]}$	$\mathcal{B}(B \to Ke^+e^-)_{[1.0-6.0]}$	$\mathcal{B}(B \to X_s e^+e^-)_{[1.0-6.0]}$	$B(B^0 \to K^{*0}e^+e^-)_{[0.03^2-1]}$
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.

Coherent Scattering(Datta, Dutta, Liao Marfatia, Strigari)

If light mediators couple to charged leptons then they couple to neutrinos also simply by $SU(2)_L$ invariance. Can be probed in coherent scattering.



A q^2 dependent form factor effect can be seen in the recoil spectrum.

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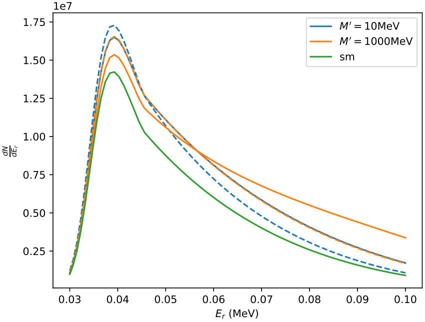


A q^2 dependent form factor effect can be seen in the recoil spectrum.

Explaining only the low q^2 bin 1711.07494

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

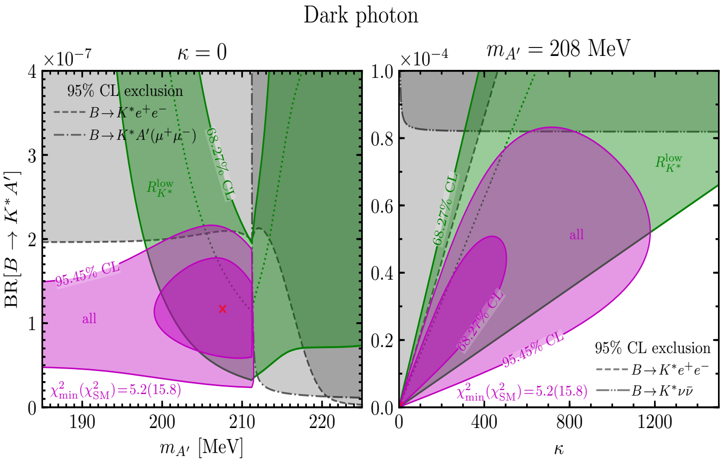
$$BR[B \to K^* \ell\ell] = BR[B \to K^* \ell\ell]_{SM} + BR[B \to K^* X] \times BR[X \to \ell\ell]$$

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.

Explaining only the low q^2 bin 1711.07494

Only interested in one bin. Dark photon with A' below the 2μ mass. LUV is just a kinematic effect in low q^2 $R_{K^{(*)}}$.



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

Familon model/ ALP:

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

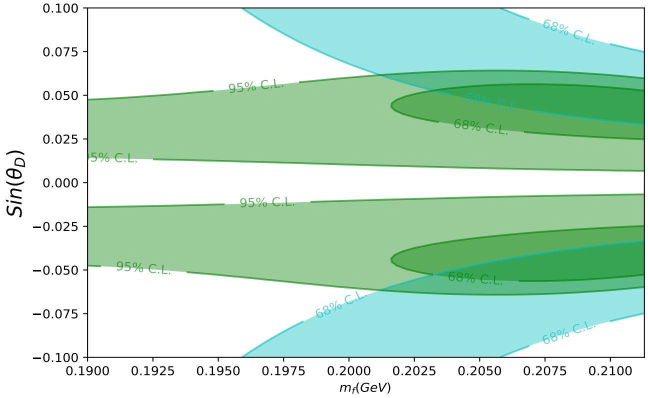
where $Q'_L = (u_L, d_L)^T$ are the left-handed quark doublets. The quarks are in the gauge basis and are indicated by primes. For the lepton couplings we write,

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

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 $F_Q >> F_L$.



$(g-2)_\mu$ problem

- LHCb signal requires The K^{*0} meson and $\ell^+\ell^-$pair are required to originate from a common vertex in order to form a B candidate.
- This gives a lower bound on the width of the particle which gives $\frac{g}{F_L}$.

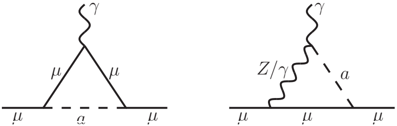
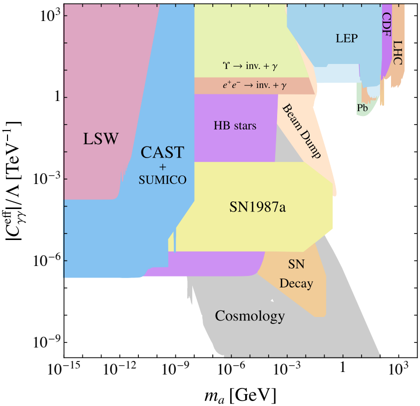


Figure: One-loop diagrams contributing to the anomalous magnetic moment of the muon.

- Constraint on $\frac{g}{F_L}$ $\Rightarrow$ too large (and opposite sign) contribution to $(g-2)_\mu$.
- This suggest other modes to $\gamma\gamma$ or invisible have to be opened up.

1708.00443



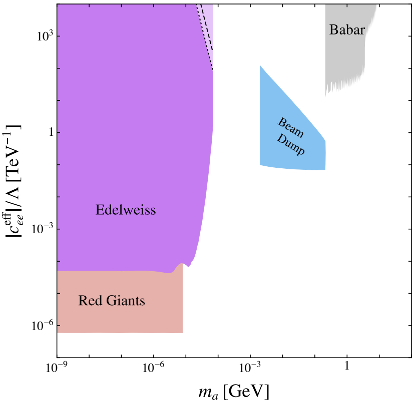


Figure: Existing constraints on the ALP–photon (left) and ALP–electron coupling (right) derived from a variety of particle physics, astro-particle physics and cosmological observations. Several of these bounds are model dependent. The BaBar constraint in the right-hand plot assumes $c_{\mu\mu} \approx c_{ee}$.

Conclusions

- Several anomalies in B decays indicating lepton non-universal interactions.
- Not all measurements can be understood with heavy new physics.
- We considered solution of the puzzles with light new physics.
- Light NP is highly constrained but some scenarios are viable. There may be some signal in low q^2 R_K measurement or in neutrino scattering.