Getting Chirality Right

single scalar leptoquarks
and lepton magnetic dipole moments

Innes Elizabeth Bigaran

Based on Bigaran, I., Volkas, R.R. Phys.Rev.D 102 (2020) 7, 075037 ○ e-Print: 2002.12544 [hep-ph]

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Overview

1.The (g-2) puzzle: SM and beyond

2. Scalar LQ solutions

3. Overcoming hurdles via a coupling ansatz

4. Outline of key results

5. Conclusions

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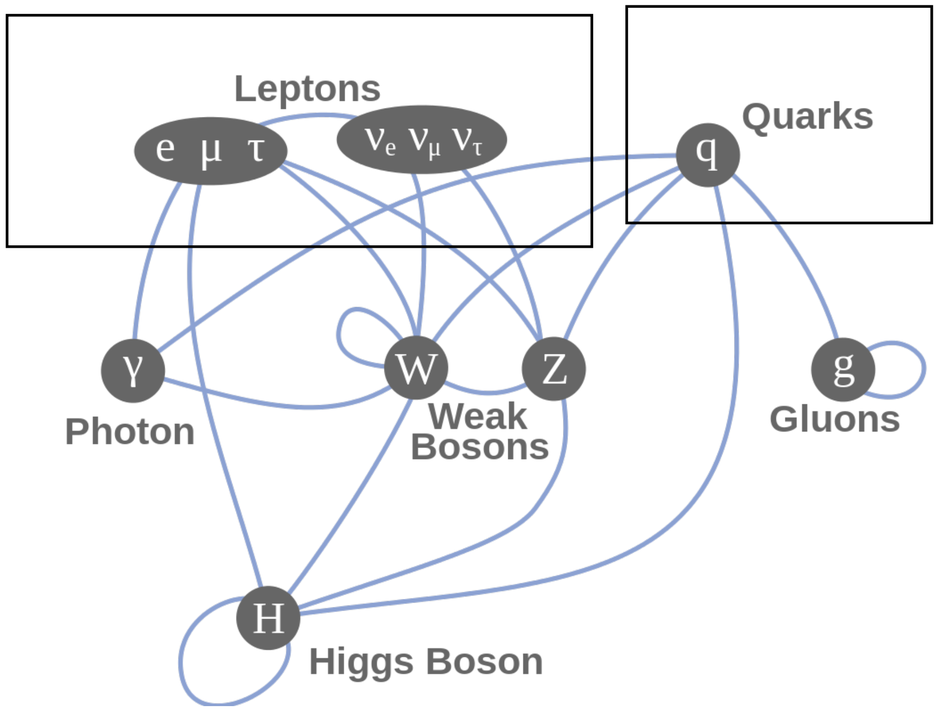
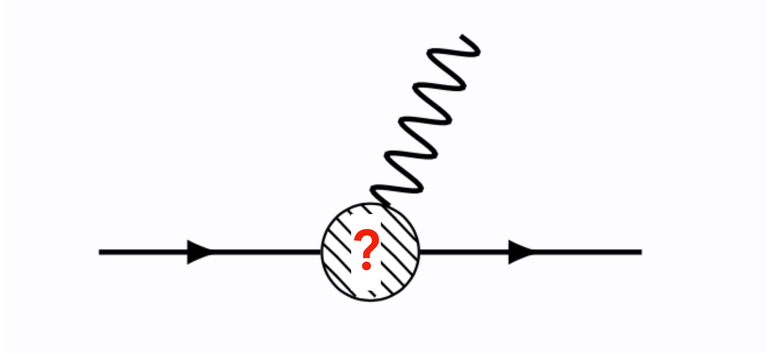
The Standard Model



- Lepton and quark sectors: blue lines indicate the interactions permitted by the SM
- Of particular interest for this talk: lepton-photon interaction

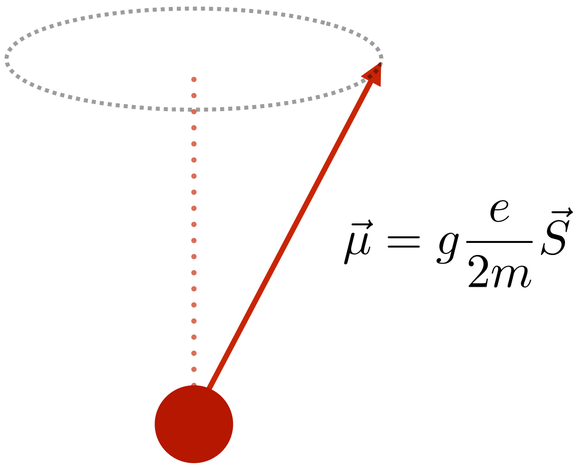


$$\mathcal{L}_{a_\ell} = \bar{\ell}\left(\boxed{a_\ell}\frac{e}{4m_\ell}\sigma_{\mu\nu} - \boxed{d_\ell}\frac{i}{2}\sigma_{\mu\nu}\gamma_5\right)\ell F^{\mu\nu}$$

Magnetic dipole moment

Electric dipole moment

The Standard Model



Here, **e** is electric charge, **m** is particle mass and **g** is a dimensionless number parameterising the size of the magnetic moment

$$\mathcal{L}_{a_\ell} = \bar{\ell}\left(\boxed{a_\ell}\frac{e}{4m_\ell}\sigma_{\mu\nu} - \boxed{d_\ell}\frac{i}{2}\sigma_{\mu\nu}\gamma_5\right)\ell F^{\mu\nu}$$

Magnetic dipole moment

Electric dipole moment

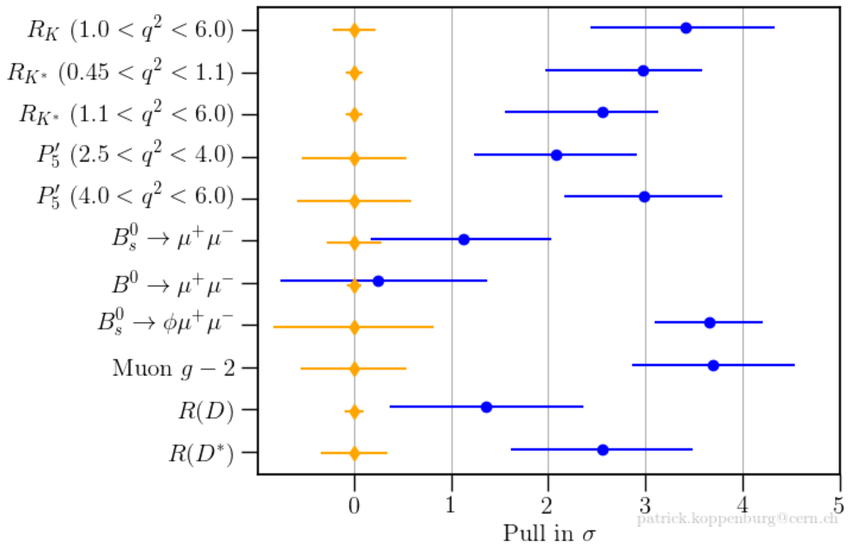
- In Pauli non-relativistic theory, for the intrinsic magnetic moment of a particle **g** can be anything
- In Dirac's wave equation approach, **g=2** for elementary spin 1/2 particles
- In full QFT, calculable corrections to the g=2 result

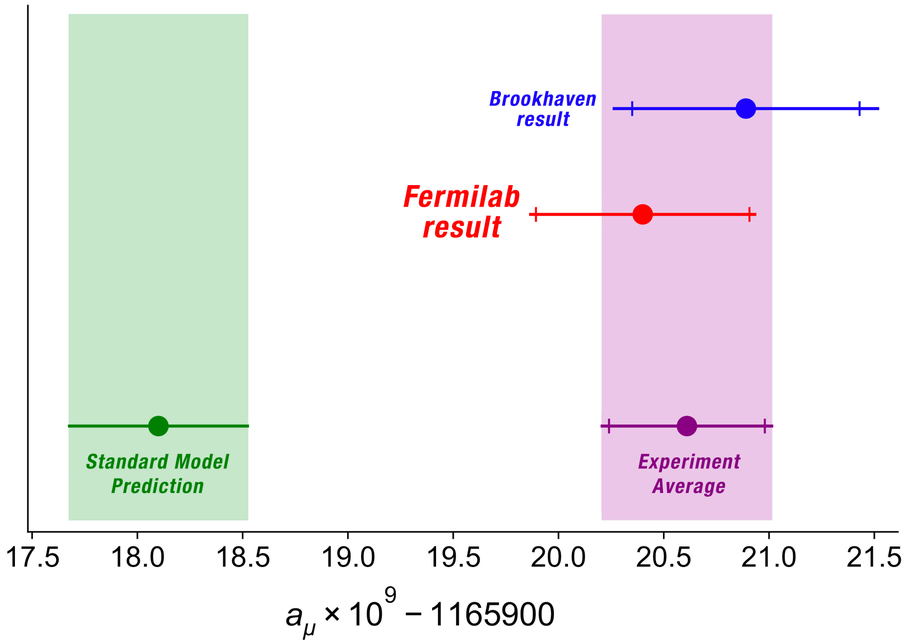
$$a_\ell = \frac{g-2}{2}$$

$$\Delta a_\ell = a_\ell^{\mathrm{exp}} - a_\ell^{\mathrm{SM}}$$

The muon g-2

- Long-standing (recently updated) anomaly — perhaps hinting at new physics that couples to muons
- Many papers investigate possible new physics explanations
- Other muonic anomalies corroborate the idea of new physics coupling to muons, e.g.





Deviation from SM prediction	Significance
$\Delta a_\mu = (2.86 \pm 0.76) \times 10^{-9}$	4.2σ

$$\Delta a_\ell = a_\ell^{\rm exp} - a_\ell^{\rm SM}$$

The electron g-2

- Established precision test for the SM and QED:
  - 'Measuring' the fine structure constant, α, assumes:

$$a_e^{\rm SM}(\alpha) = a_e^{\rm Exp} \implies \alpha$$

  - This would assume no anomaly! So we require a determination of α independent of g-2.
  - Two conflicting experimental results for α, via interferometry experiments, disagree by more than 5 sigma:
    1. Using Cs, anomaly <u>opposite sign</u> to the muon
    2. Using Rb, anomaly (?) in the same sign as the muon

Deviation from SM prediction	Significance
$\Delta a_\mu = (2.86 \pm 0.76) \times 10^{-9}$	4.2σ
$\Delta a_e^{\rm Cs} = -(0.88 \pm 0.36) \times 10^{-12}$ Parker et al 1812.04130	2.5σ
$\Delta a_e^{\rm Rb} = (4.8 \pm 3.0) \times 10^{-13}$ Morel et al 2020, INSPIRE: 1837309	1.6σ

So far, no resolution to this disagreement

The g-2 anomalies

$$\mathcal{L}_{a_\ell} = \bar{\ell}\left(a_\ell \frac{e}{4m_\ell}\sigma_{\mu\nu} - d_\ell \frac{i}{2}\sigma_{\mu\nu}\gamma_5\right)\ell F^{\mu\nu}$$

Magnetic dipole moment

$$\Delta a_\ell = a_\ell^{\text{exp}} - a_\ell^{\text{SM}}$$

Deviation from SM prediction	Significance
$\Delta a_\mu = (2.86 \pm 0.76) \times 10^{-9}$	4.2σ
$\Delta a_e = -(0.88 \pm 0.36) \times 10^{-12}$	$2.5\,\sigma$

While electron g-2 is still unresolved, we focus on the more significant anomaly, also because it is a more interesting problem to tackle.

The Problem

- Anomalies in the electron and muon magnetic dipole moments
- Deviations have **opposite sign**, but comparable magnitude
- Could there be a common origin via flavour-violating couplings?

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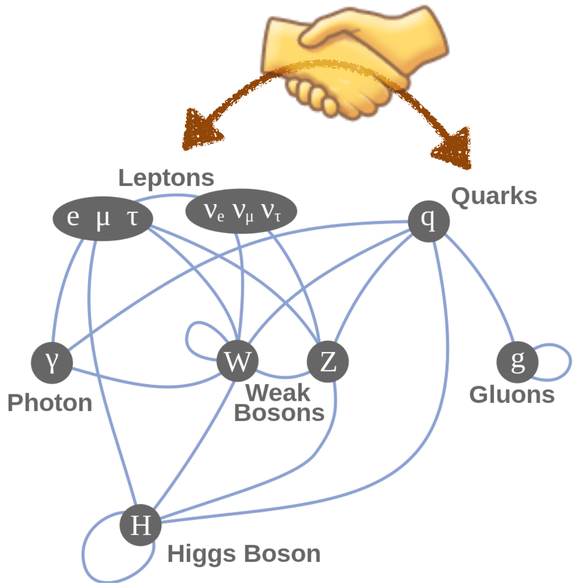


Scalar LQ models

Symbol	$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
$\tilde{S}_1$	$(\mathbf{3}, \mathbf{1}, -4/3)$
S_1	$(\mathbf{3}, \mathbf{1}, -1/3)$
S_3	$(\mathbf{3}, \mathbf{3}, -1/3)$
$\overline{S}_1$	$(\mathbf{3}, \mathbf{1}, 2/3)$
R_2	$(\mathbf{3}, \mathbf{2}, 7/6)$
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, 1/6)$

- Leptoquarks (LQ) are hypothetical particles which directly couple SM leptons and quarks
- There are a finite set of scalar LQ (for a review, see arXiv: 1603.04993)
- LQ masses and Yukawa couplings between SM and BSM fields are generically *free* parameters, e.g.

Left-handed coupling

$$\mathcal{L}_\ell = \overline{\ell^{(c)}} \left[y^R P_R + y^L P_L \right] q \, \phi^\dagger + h.c.$$

Right-handed coupling

Mixed chiral scalar LQs

Left-handed coupling

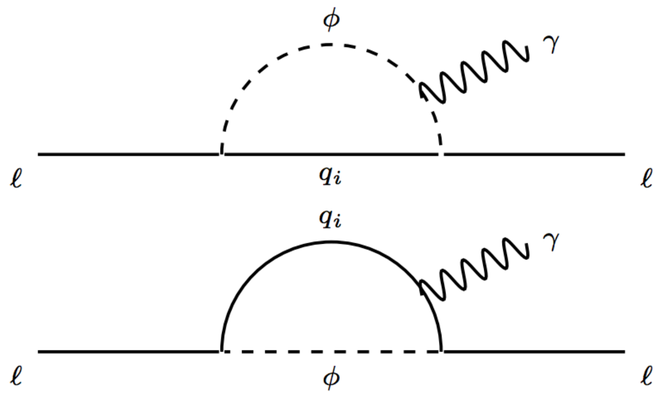
$$\mathcal{L}_\ell = \overline{\ell^{(c)}} \left[y^R P_R + y^L P_L \right] q\, \phi^\dagger + h.c.$$

Right-handed coupling

Symbol	$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$	Mixed chiral
$\tilde{S}_1$	$(\mathbf{3}, \mathbf{1}, -4/3)$	✗
S_1	$(\mathbf{3}, \mathbf{1}, -1/3)$	✓
S_3	$(\mathbf{3}, \mathbf{3}, -1/3)$	✗
$\overline{S}_1$	$(\mathbf{3}, \mathbf{1}, 2/3)$	✗
R_2	$(\mathbf{3}, \mathbf{2}, 7/6)$	✓
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, 1/6)$	✗

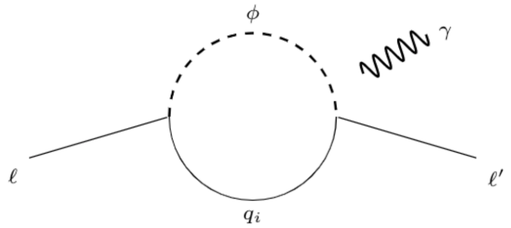
The highlighted LQ are mixed-*chiral*

- Mixed-chiral LQ have both L and R couplings
- *Could* generate sizeable corrections to (g-2) at one-loop level (enhanced via internal quark-mass insertion)

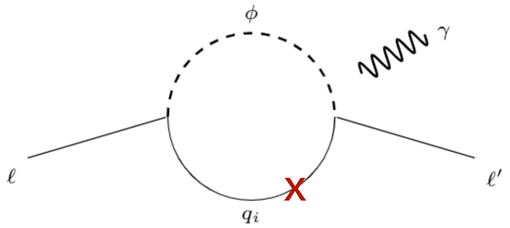


Mixed chiral scalar LQs

$$\mathcal{L}_\ell = \overline{\ell^{(c)}} \left[y^R P_R + y^L P_L \right] q \, \phi^\dagger + h.c.$$



sign-definite



variable sign

S_1	$(\mathbf{3}, \mathbf{1}, -1/3)$
R_2	$(\mathbf{3}, \mathbf{2}, 7/6)$

$$\Delta a_\ell = -\frac{3 m_\ell}{8\pi^2 m_\phi^2} \sum_q \Big[\underbrace{m_\ell (|y_\ell^R|^2 + |y_\ell^L|^2)\kappa}_{\text{sign-definite}} + \underbrace{m_q \mathrm{Re}(y_\ell^{L*} y_\ell^R)\kappa'}_{\text{variable sign}} \Big]$$

For these two LQ, we can exploit this variable sign term to give flavour-dependent, opposite sign, corrections

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A flavour ansatz

Yukawa couplings with SM fields are generally *free* parameters, so we have some choices to make.

- I will preface this next discussion by saying that the what I'm about to discuss **isn't** showing a basis-dependence of a physical result (that would be ludicrous!)
- The argument here is that: *a choice of basis can affect how clear it is to make definitive claims about a model's viability.*

A flavour ansatz

How easy is it to turn on or off couplings between particular flavours?

The answer lies in the choice of *where* I put the CKM.

$$\mathcal{L}_{\text{int}}^{S_1} = \left(\overline{L_L^c}\lambda_{LQ}Q_L + \overline{e_R^c}\lambda_{eu}u_R\right) S_1^\dagger + h.c.,$$

EWSB and rotating fields into mass-eigenstates

Recalling that: $V = \mathfrak{L}_u^\dagger \mathfrak{L}_d$

1. $\mathfrak{R}_e\lambda_{eu}\mathfrak{R}_u \mapsto y^{Seu}$, $\boxed{\mathfrak{L}_e\lambda_{LQ}\mathfrak{L}_u \mapsto y^{SLQ}}$

$$\mathcal{L}^{S_1} \supset y_{ij}^{SLQ}\left[\overline{e_{L,i}^c}u_{L,j} - V_{jk}\,\overline{\nu_{L,i}^c}d_{L,k}\right] S_1^\dagger$$

'Up-type'

$$+ y_{ij}^{Seu}\overline{e_{R,i}^c}u_{R,j}S_1^\dagger + h.c.,$$

2. $\mathfrak{R}_e\lambda_{eu}\mathfrak{R}_u \mapsto y^{Seu}$, $\boxed{\mathfrak{L}_e\lambda_{LQ}\mathfrak{L}_d \mapsto y'^{SLQ},}$

$$\mathcal{L}^{S_1} \supset y_{ij}'^{SLQ}\left[V_{jk}^\dagger\overline{e_{L,i}^c}u_{L,k} - \overline{\nu_{L,i}^c}d_{L,j}\right] S_1^\dagger$$

'Down-type'

$$+ y_{ij}^{Seu}\overline{e_{R,i}^c}u_{R,j}S_1^\dagger + h.c.,$$

‘Up’ and ‘down’ type bases

1. $\mathfrak{R}_e \lambda_{eu} \mathfrak{R}_u \mapsto y^{Seu}$, $\boxed{\mathfrak{L}_e \lambda_{LQ} \mathfrak{L}_u \mapsto y^{SLQ}}$

$$\mathcal{L}^{S_1} \supset y^{SLQ}_{ij} \left[\overline{e^c_{L,i}} u_{L,j} - V_{jk}\, \overline{\nu^c_{L,i}} d_{L,k} \right] S_1^\dagger + y^{Seu}_{ij} \overline{e^c_{R,i}} u_{R,j} S_1^\dagger + h.c.,$$

‘Up-type’

2. $\mathfrak{R}_e \lambda_{eu} \mathfrak{R}_u \mapsto y^{Seu}$, $\boxed{\mathfrak{L}_e \lambda_{LQ} \mathfrak{L}_d \mapsto y'^{SLQ}}$,

$$\mathcal{L}^{S_1} \supset y'^{SLQ}_{ij} \left[V^\dagger_{jk} \overline{e^c_{L,i}} u_{L,k} - \overline{\nu^c_{L,i}} d_{L,j} \right] S_1^\dagger + y^{Seu}_{ij} \overline{e^c_{R,i}} u_{R,j} S_1^\dagger + h.c.,$$

‘Down-type’

- Now imagine we want to switch-off a particular coupling: e.g. as above

	LH coupling between electron and top-quark	
1.	y^{SLQ}_{13} =0	Simple
2.	$y'^{SLQ}_{1j} V^\dagger_{j3}$ =0	Messy

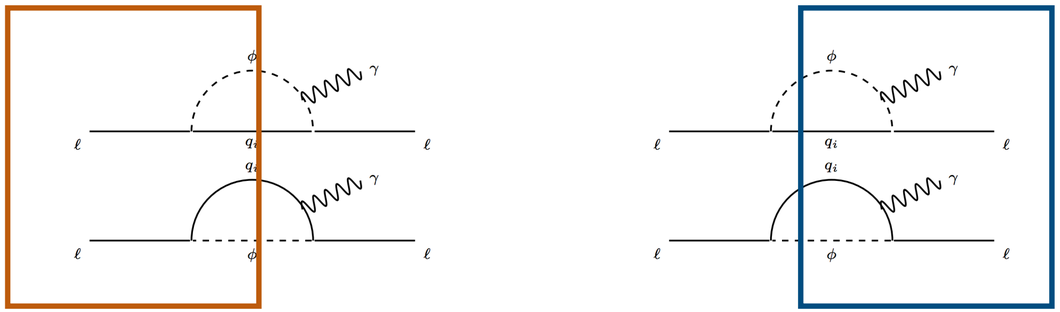
We should guide our basis choice by looking at what couplings we want to control the most — motivated by observables and constraints

A downside of the ‘down’ type basis

$$\Delta a_\ell = -\frac{3m_\ell}{8\pi^2 m_\phi^2}\sum_q \Big[m_\ell(|y_\ell^R|^2 + |y_\ell^L|^2)\kappa + m_q \mathrm{Re}(y_\ell^{L*} y_\ell^R)\kappa' \Big]$$

sign-definite

variable sign



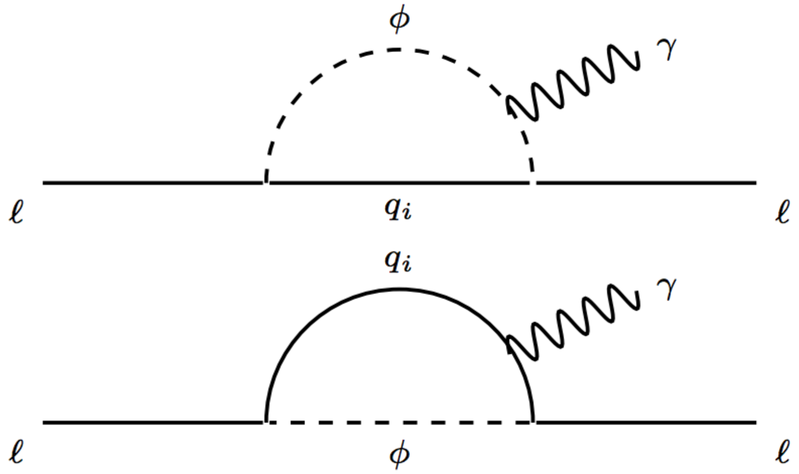
$$\mu \to e\gamma$$

- If we *did* work in the down-type quark basis, this makes it hard for us to determine a viable zero texture for the Yukawas
- Why? It turns out that because of:
  - A. The enhancement of a top-quark in the loop
  - B. The strength of the MEG constraint $\mu \to e\gamma$

Even if just a `small’ coupling to the top is generated for both lepton flavours, we hit the MEG limit —- **invalidating the model**

You can see how one may be tempted to rule out all scalar LQ models if you only looked in the down-type basis.

Establishing the models



$$\mathbf{y}^L \sim \begin{pmatrix} 0 & \blacksquare & 0 \\ 0 & 0 & \blacksquare \\ 0 & 0 & 0 \end{pmatrix}, \quad \mathbf{y}^R \sim \begin{pmatrix} 0 & \blacksquare & 0 \\ 0 & 0 & \blacksquare \\ 0 & 0 & 0 \end{pmatrix}$$

$u \quad c \quad t$

$e \quad \mu \quad \tau$

Adopting the ‘up-type’ basis :

- Contribution to (g-2) of the electron is via a **charm**-containing loop
- Contribution to (g-2) of the muon is via a **top**-containing loop
- Constraints from MEG in particular avoided by having different intermediate SM quarks coupling for each g-2
- Restrict all NP couplings to <u>real values</u>.

$$\Delta a_\ell^{S_1} \sim -\frac{m_\ell m_q}{4\pi^2 m_{S_1}^2}\left[\frac{7}{4} - 2\log\left(\frac{m_{S_1}}{m_q}\right)\right]\mathrm{Re}(y_{\ell q}^{L*} y_{\ell q}^{R}),$$

$$\Delta a_\ell^{R_2} \sim \frac{m_\ell m_q}{4\pi^2 m_{R_2}^2}\left[\frac{1}{4} - 2\log\left(\frac{m_{R_2}}{m_q}\right)\right]\mathrm{Re}(y_{\ell q}^{L*} y_{\ell q}^{R}),$$

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Single mass scans

Now that we have two viable models, assessing constraints using two different scan methods:

Method 1: Fixed RH couplings around (g-2)

1. Logarithmically sample 2 x LH couplings

2. Calculate RH couplings according to (g-2), outputting real-value generating point closest to central values

3. Check generated RH coupling under perturbativity constraint.

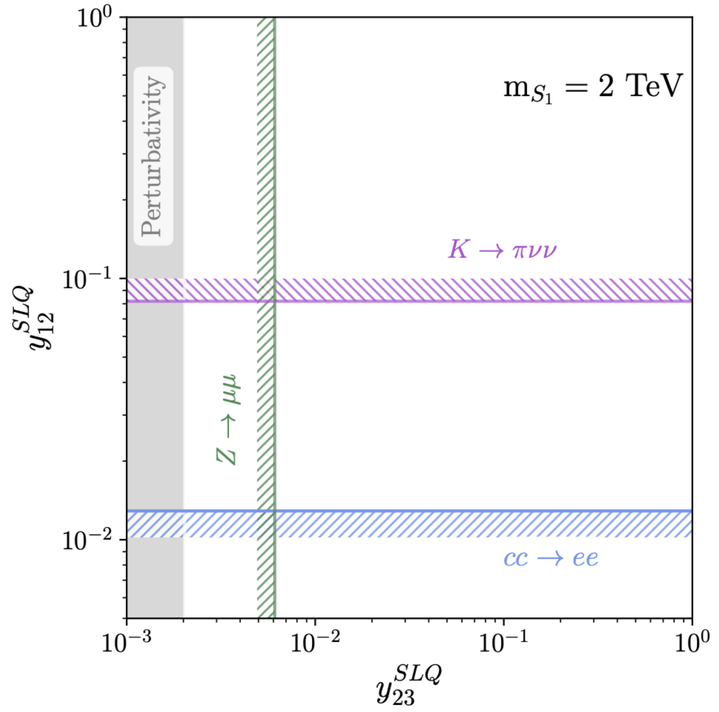
4. Check other constraints

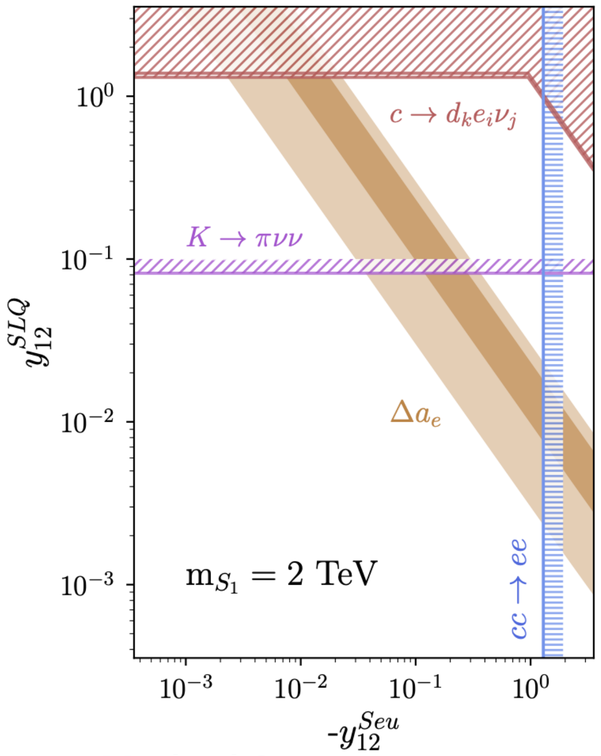
Method 2: decoupled electron and muon sectors

separately sampling LH and RH couplings logarithmically

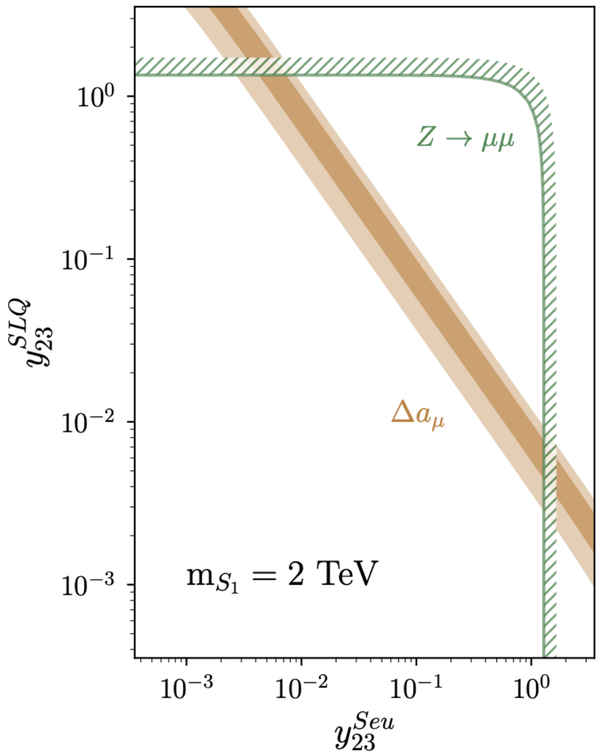
S1 Leptoquark: benchmark study

Method 1



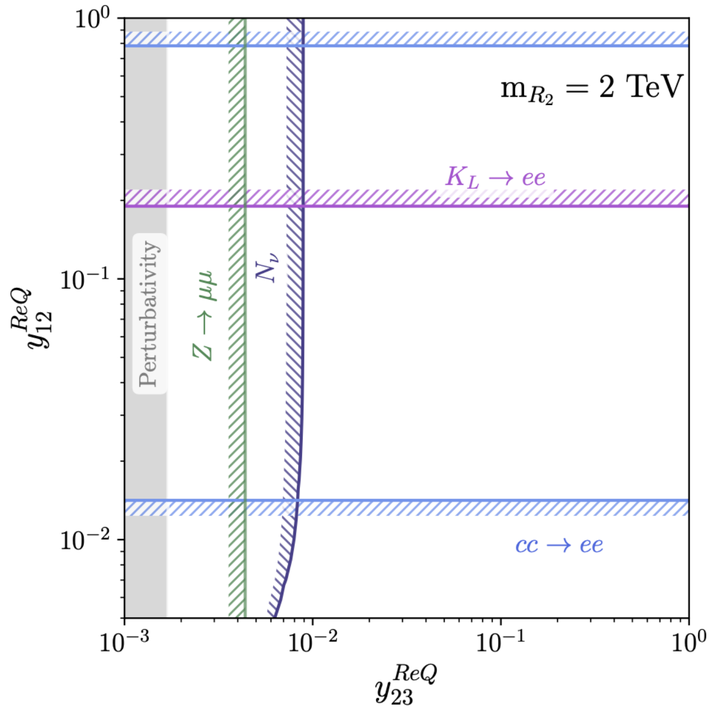


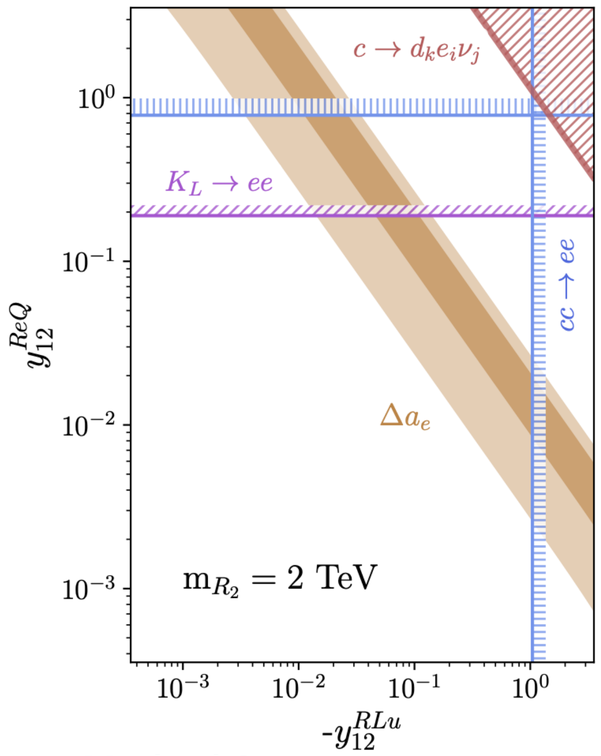
Method 2



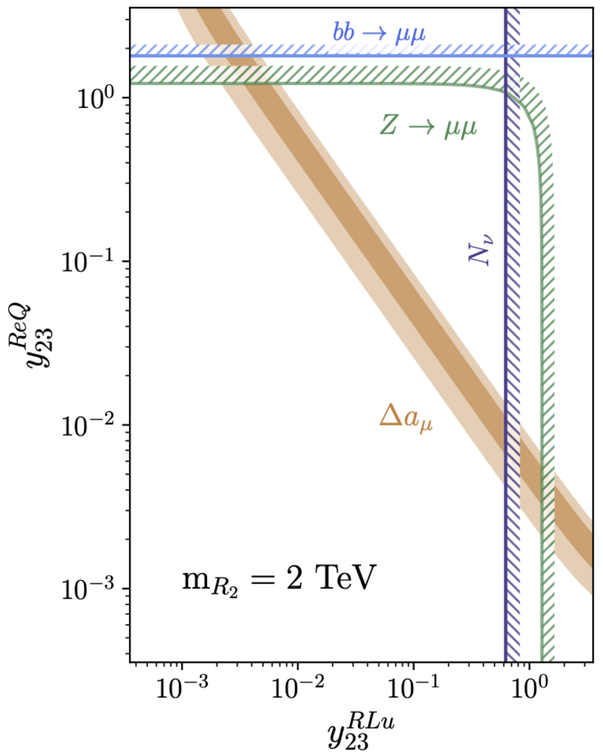
R2 Leptoquark: benchmark study

Method 1





Method 2



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Conclusions

Based on *Phys.Rev.D* 102 (2020) 7, 075037 · e-Print: 2002.12544 [hep-ph]

- We have argued the viability of single LQ simultaneous solutions to anomalies in g-2 of the electron and muon.
- Identified the two mixed chiral scalar LQ, capable of generating sign-dependent contributions to leptonic g-2 observables.
- LFV constraints can be avoided by allowing contribution to the electron g-2 from charm-containing loops, and muon g-2 from top-containing loops.
- Extending to complex couplings motivates consideration of EDMs as well as g-2
  (manuscript in preparation)

Back-up Slides

Process	Observable	Limits
$Z \to \ell_i \ell_j$	$\{g_L^\mu, g_R^\mu\}$	$\{-0.2689(11), +0.2323(13)\}$
$Z \to \nu\nu$	N_ν	2.9840(82)
$D^\pm \to e\nu$	Br	$< 8.8 \times 10^{-6}$
$D_s^\pm \to e\nu$	Br	$< 8.3 \times 10^{-5}$
$K^+ \to \pi^+\nu\nu$	Br	$(1.7 \pm 1.1) \times 10^{-10}$
$K_L^0 \to e^+e^-$	Br	$(9^{+6}_{-4}) \times 10^{-12}$
$pp \to \ell\ell$	$\lvert y_{12}^{Seu}\rvert$	$< 0.648\ m_\phi/\text{TeV}$
	$\lvert y_{12}^{SLQ}\rvert$	$< 0.537\ m_\phi/\text{TeV}$
[44]	$\lvert y_{12}^{ReQ}\rvert$	$< 0.393\ m_\phi/\text{TeV}$
	$\lvert y_{12}^{RLu}\rvert$	$< 0.524\ m_\phi/\text{TeV}$
	$\lvert y_{23}^{ReQ}\rvert$	$< 0.904\ m_\phi/\text{TeV}$
$c \to d_k \bar{e}_i \nu_j$	$\epsilon_{V_L}^{111}$	$\in [-0.52, 0.86] \times 10^{-2}$
	$\epsilon_{V_L}^{112}$	$\in [-0.28, 0.59] \times 10^{-2}$
[41]	$\{\lvert\epsilon_{V_L}^{121}\rvert, \lvert\epsilon_{V_L}^{122}\rvert\}$	$\{< 0.67, < 0.42\} \times 10^{-2}$
	$\{\lvert\epsilon_{S_L}^{111}\rvert, \lvert\epsilon_{S_L}^{112}\rvert\}$	$\{< 0.72, < 0.43\} \times 10^{-2}$
	$\{\lvert\epsilon_{S_L}^{211}\rvert, \lvert\epsilon_{S_L}^{212}\rvert\}$	$\{< 1.1, < 0.68\} \times 10^{-2}$
	$\{\lvert\epsilon_T^{111}\rvert, \lvert\epsilon_T^{112}\rvert\}$	$\{< 4.3, < 2.8\} \times 10^{-3}$
	$\{\lvert\epsilon_T^{211}\rvert, \lvert\epsilon_T^{212}\rvert\}$	$\{< 6.6, < 4.0\} \times 10^{-3}$

Model Lagranians

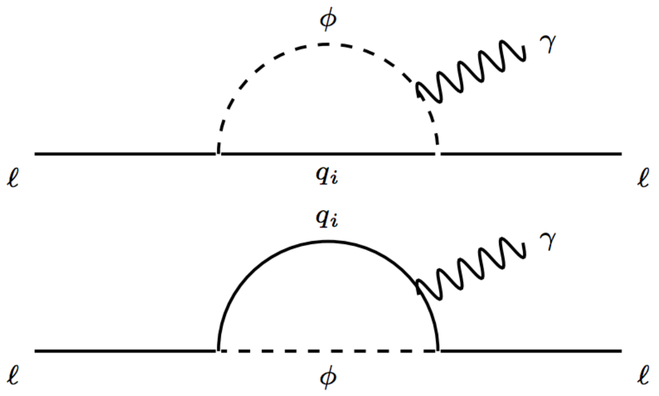
$$\mathcal{L}^{S_1} \supset y_{ij}^{SLQ}\left[\overline{e_{L,i}^c} u_{L,j} - V_{jk}\,\overline{\nu_{L,i}^c} d_{L,k}\right] S_1^\dagger + y_{ij}^{Seu}\overline{e_{R,i}^c} u_{R,j} S_1^\dagger + h.c.$$

$$\mathcal{L}^{R_2} \supset y_{ij}^{RLu}\left[\overline{\nu_{L,i}} u_{R,j} R_2^{2/3,\dagger} - \overline{e_{L,i}} u_{R,j} R_2^{5/3,\dagger}\right] + y_{ij}^{ReQ}\overline{e_{R,i}}\left[u_{L,j} R_2^{5/3,\dagger} + V_{jk} d_{L,k} R_2^{2/3,\dagger}\right]$$

Which zero texture?

$$\Delta a_\ell = -\frac{3m_\ell}{8\pi^2 m_\phi^2}\sum_q \Big[m_\ell(|y_\ell^R|^2+|y_\ell^L|^2)\kappa + m_q \mathrm{Re}(y_\ell^{L*}y_\ell^R)\kappa'\Big].$$

$$\mathcal{L}_\ell = \overline{\ell^{(c)}}\ \left[y^R P_R + y^L P_L\right]\ q\ \phi^\dagger + h.c.$$



- To ensure we have the mass-enhanced mixed-chiral contribution, the zero **texture** of the LH and RH Yukawas should be identical

$$\text{Texture 1} \sim \begin{pmatrix} 0 & 0 & \blacksquare \\ 0 & \blacksquare & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad \text{Texture 2} \sim \begin{pmatrix} 0 & \blacksquare & 0 \\ 0 & 0 & \blacksquare \\ 0 & 0 & 0 \end{pmatrix}.$$

Charm- muon
Top- electron

OR

Charm- electron
Top- muon

Charmphilic solution to muon g-2 with leptoquarks, arxiv:1812.06851. **Only possible to do muon g-2 within two sigma.**