Getting Chirality Right | single scalar leptoquarks and lepton magnetic dipole moments

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

Phenomenology 2021 Symposium, University of Pittsburgh

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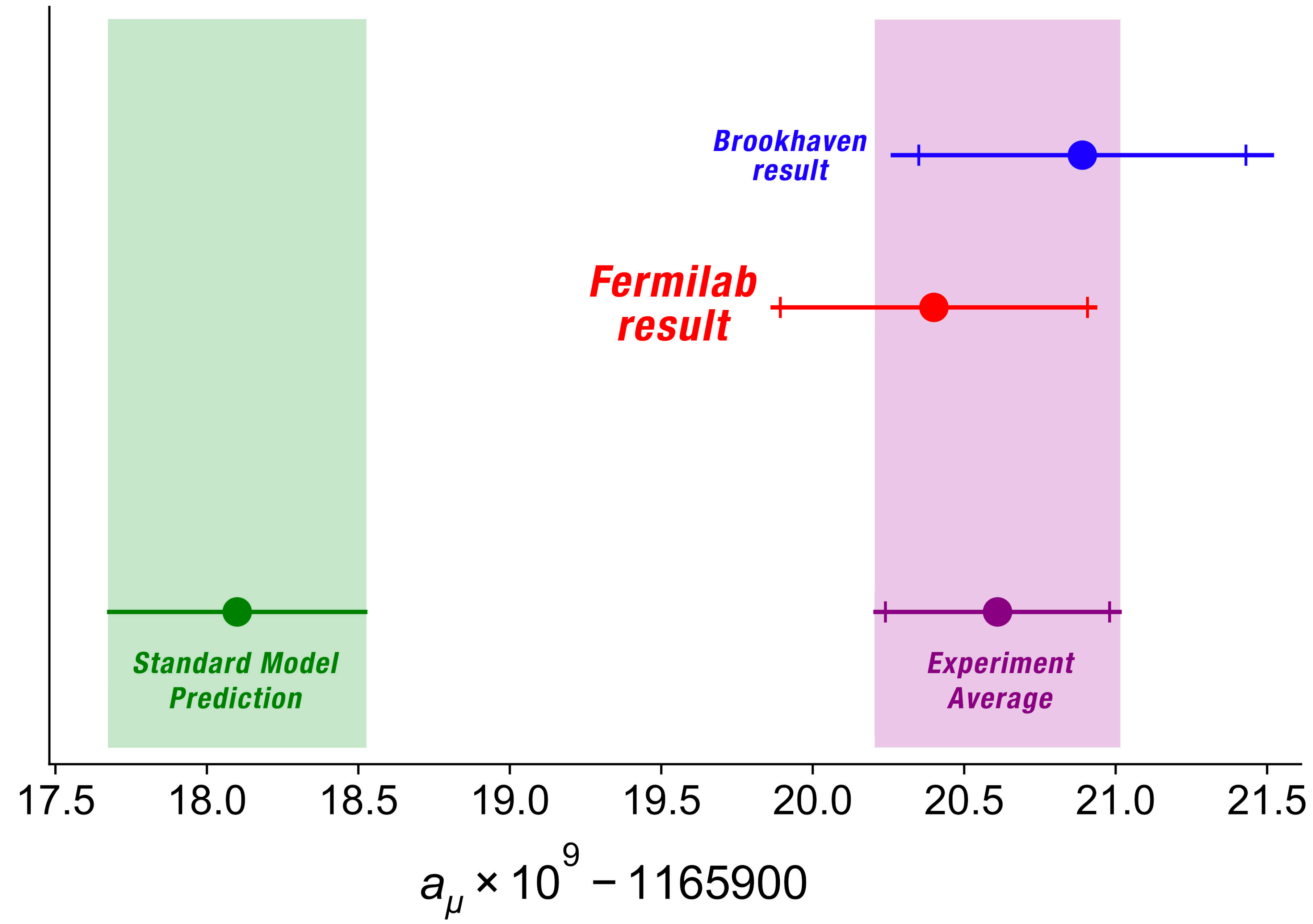
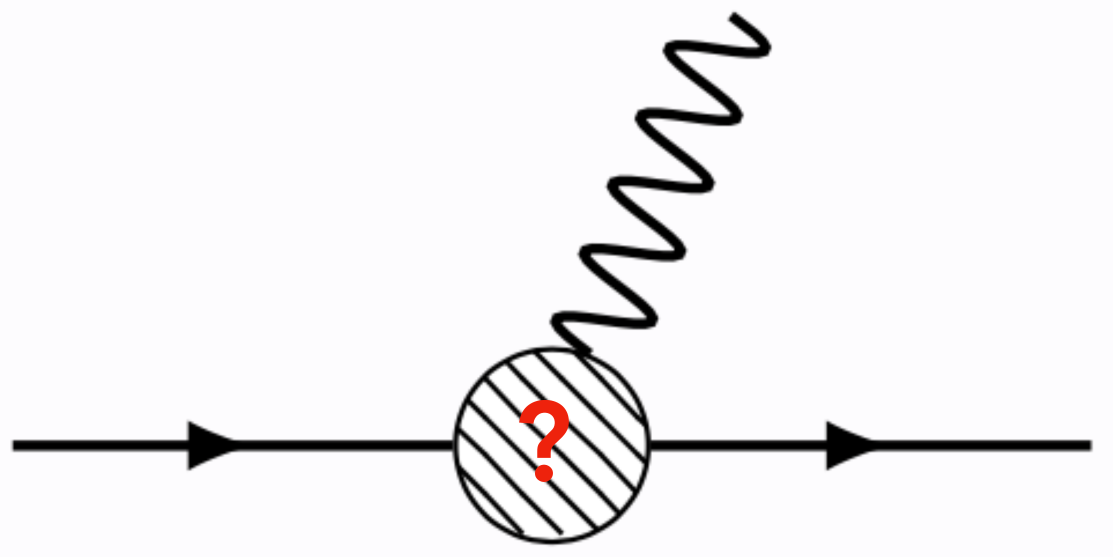
(g-2) of the muon

- I hopefully won't need to explain this in too much detail, as it has made waves in recent months.
- Long-standing anomaly — perhaps hinting at new physics that couples to muons
- Many papers investigate possible new physics explanations
- Other muonic anomalies, e.g. b -> s mu mu, corroborate the idea of LFV in BSM physics





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

(g-2) of the electron

- 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 opposite sign 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

(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

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

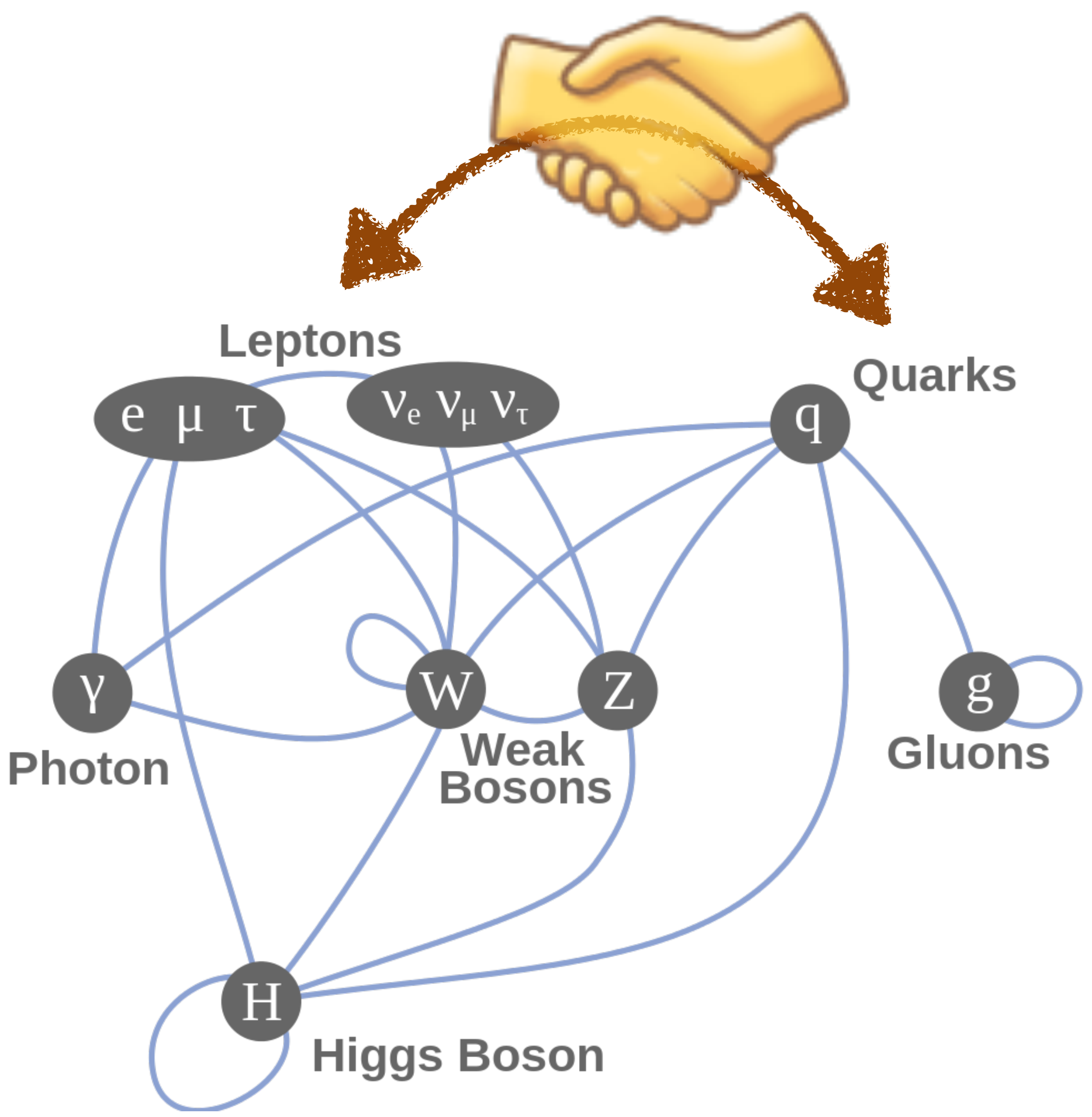
Deviation from SM prediction	Significance
$\Delta a_\mu = (2.86 \pm 0.76) \times 10^{-9}$	4.2σ
$\Delta a_e = -(0.88 \pm 0.36) \times 10^{-12}$	$2.5\ \sigma$

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?

Scalar LQs



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	$(\mathbf{3}, \mathbf{3}, -1/3)$
$\bar{S}_1$	$(\mathbf{3}, \mathbf{1}, 2/3)$
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 <u>scalar</u> 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

Chiral scalar LQs

Left-handed coupling

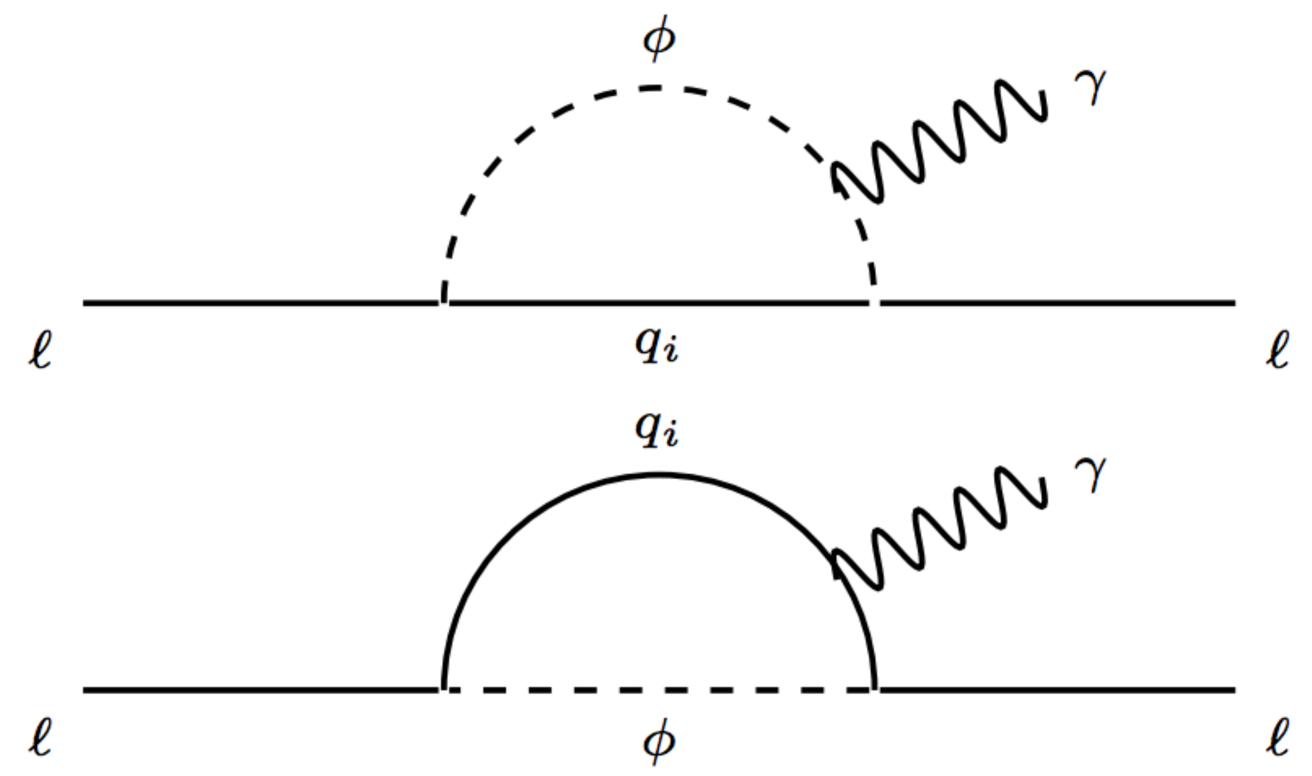
$$\mathcal{L}_\ell = \overline{\ell^{(c)}} \left[y^R P_R + y^L P_L \right] q\, \phi^\dagger + h.c.$$

Right-handed coupling

Symbol	$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$	$(g-2)_\ell$ at 1L
$\tilde{S}_1$	$(\mathbf{3}, \mathbf{1}, -4/3)$	✗
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	$(\mathbf{3}, \mathbf{2}, 7/6)$	✓
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, 1/6)$	✗

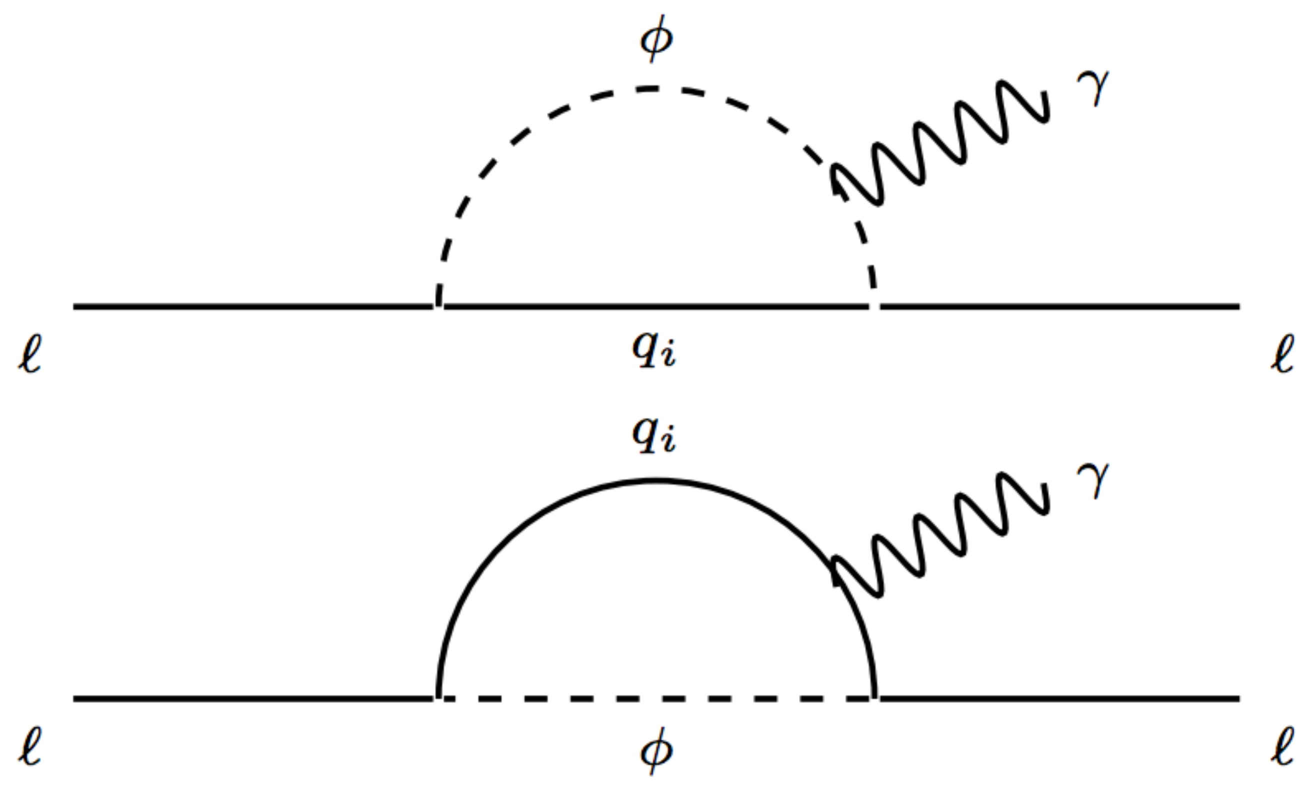
The highlighted LQ are *(maximally) chiral*

- Maximally-chiral (also just called 'chiral') LQ have both L and R couplings
- *Could* generate sizeable corrections to (g-2) at one-loop via:



Chiral scalar LQs

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



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

sign-definite

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

$$+ m_q \mathrm{Re}(y_\ell^{L*} y_\ell^R)\kappa' \Big]$$

variable sign

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

Flavour ansatz

- 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!)

- My argument here is that: *a choice of basis can affect how clear it is to make definitive claims about a model's viability.*

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.

$$\mathcal{L}^{S_1}_{\rm int} = \left(\overline{L^c_L}\lambda_{LQ}Q_L + \overline{e^c_R}\lambda_{eu}u_R\right) S_1^\dagger + h.c.,$$

EWSB and rotating fields into mass-eigenstates

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

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

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

'Up-type'

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

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

'Down-type'

‘Up-type’ and ‘down-type’ bases

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

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

‘Up-type’

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

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

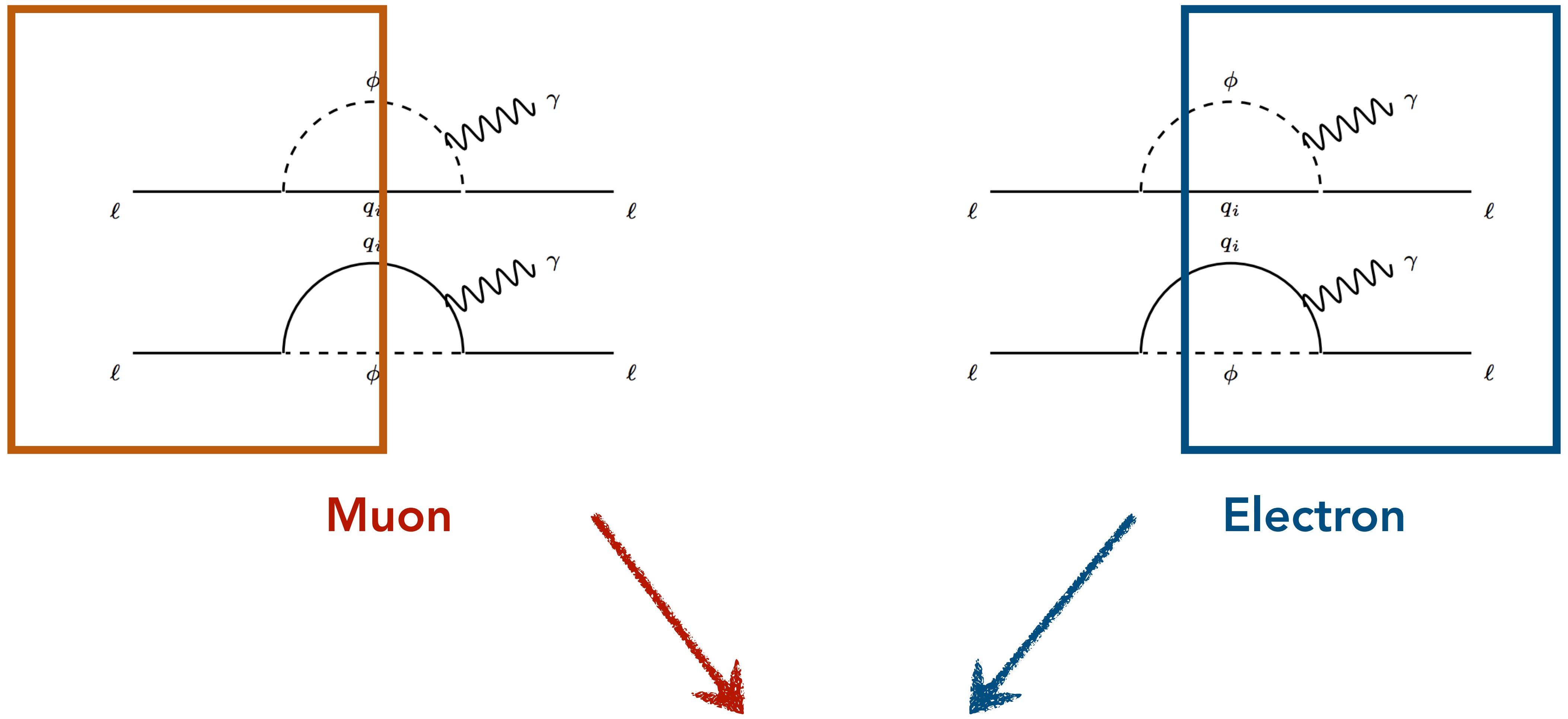
‘Down-type’

- 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



$$\mu \to e\gamma$$

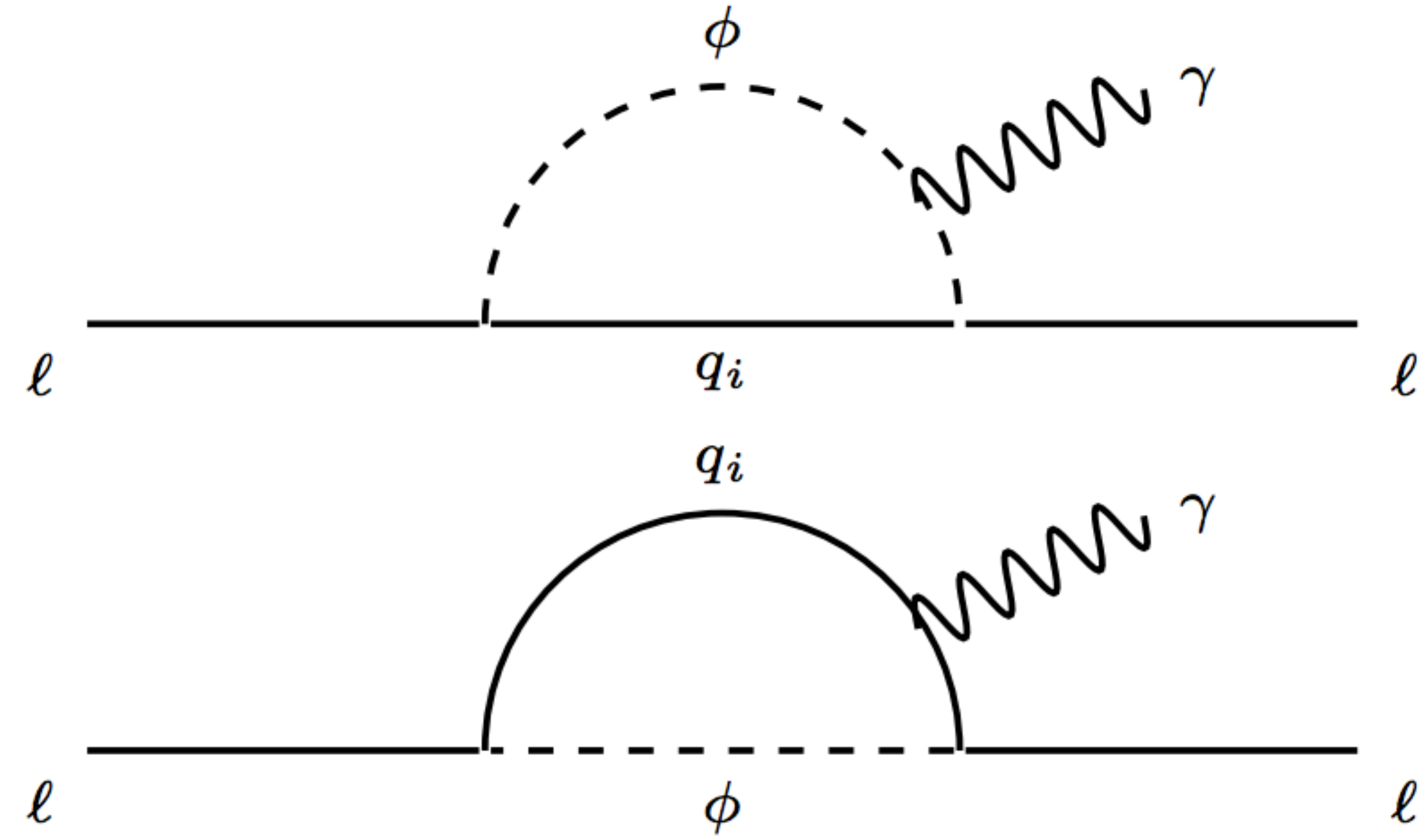
- If we *did* work in the down-type quark basis, this makes it hard for us to determine a viable zero texture for the Yukawas
- Why? It turns out that because of:

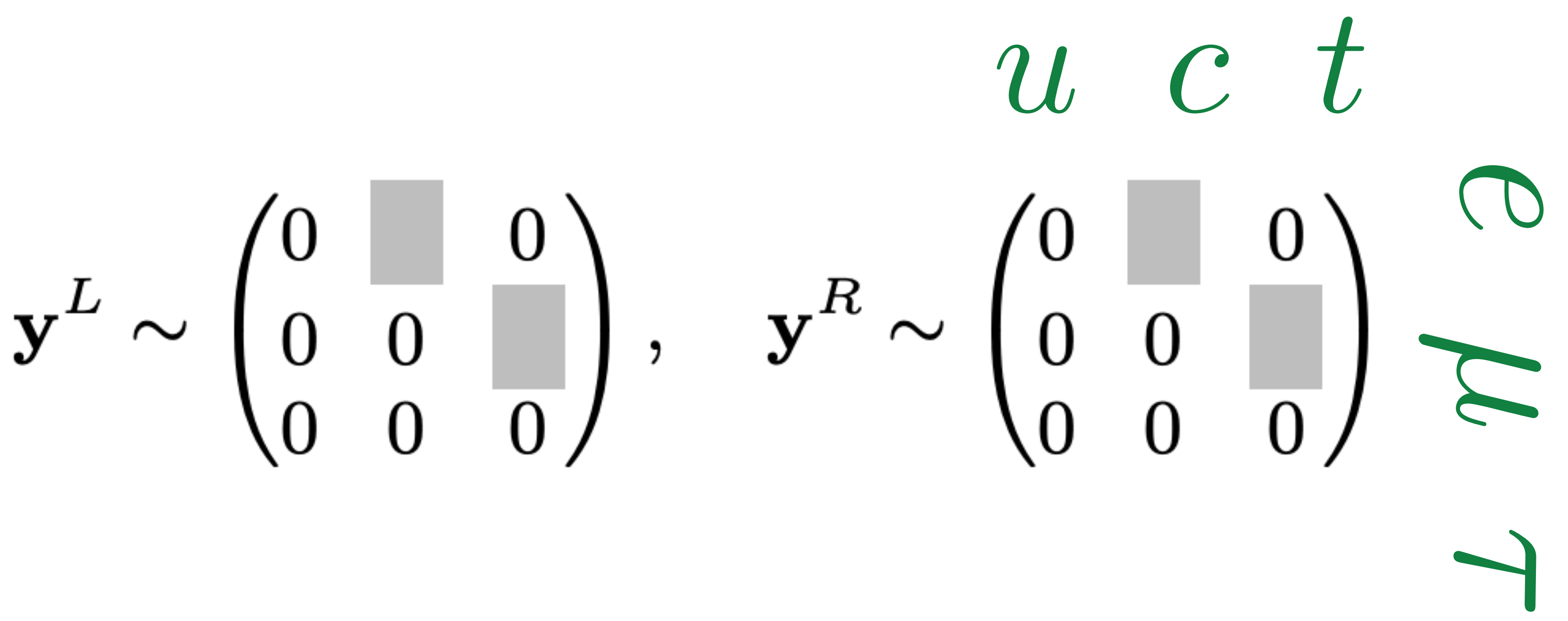
  A. The enhancement of a top-quark in the loop

  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

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 real values.

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

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

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.

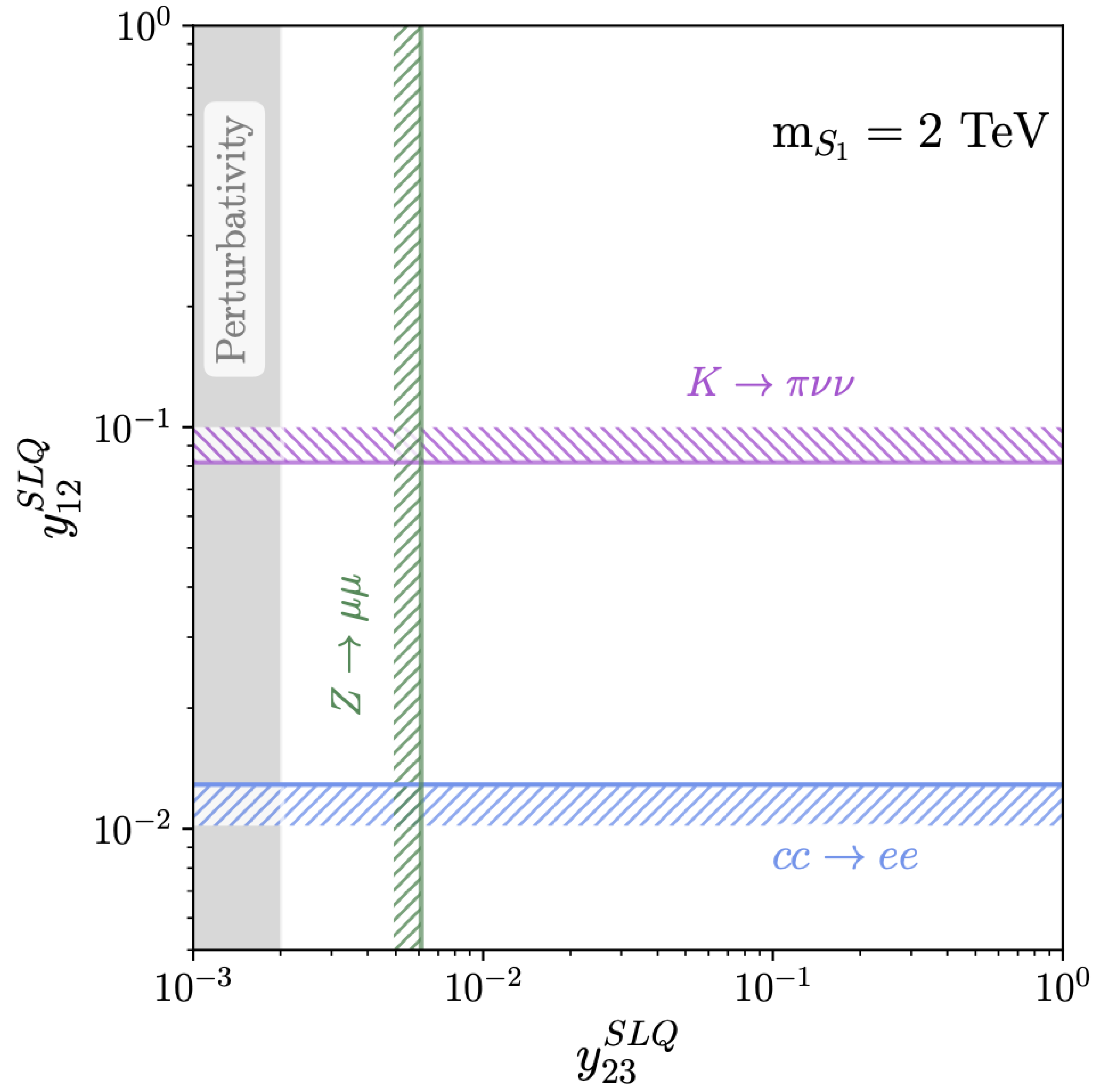
4. Check other constraints

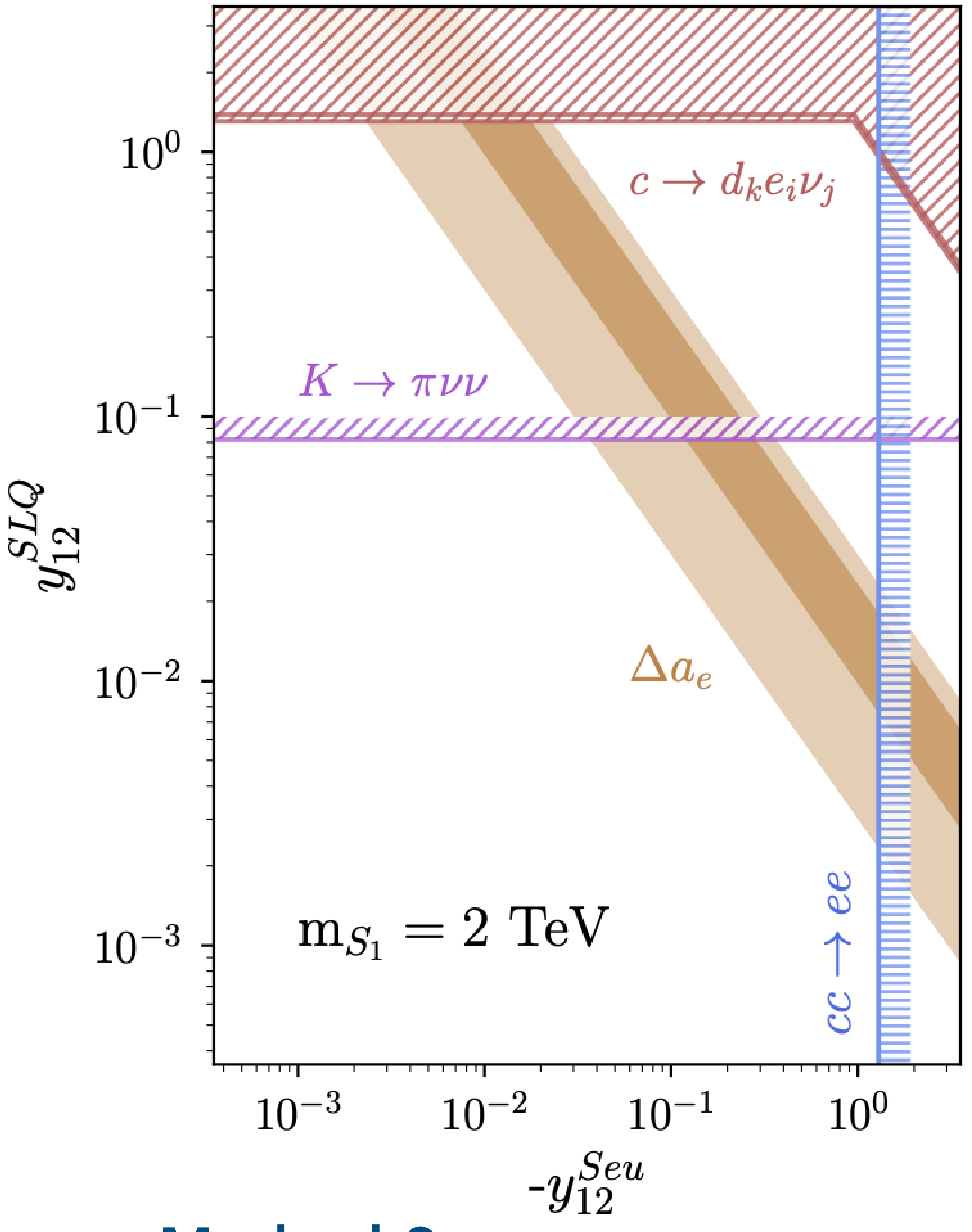
Method 2: decoupled electron and muon sectors

separately sampling LH and RH couplings logarithmically

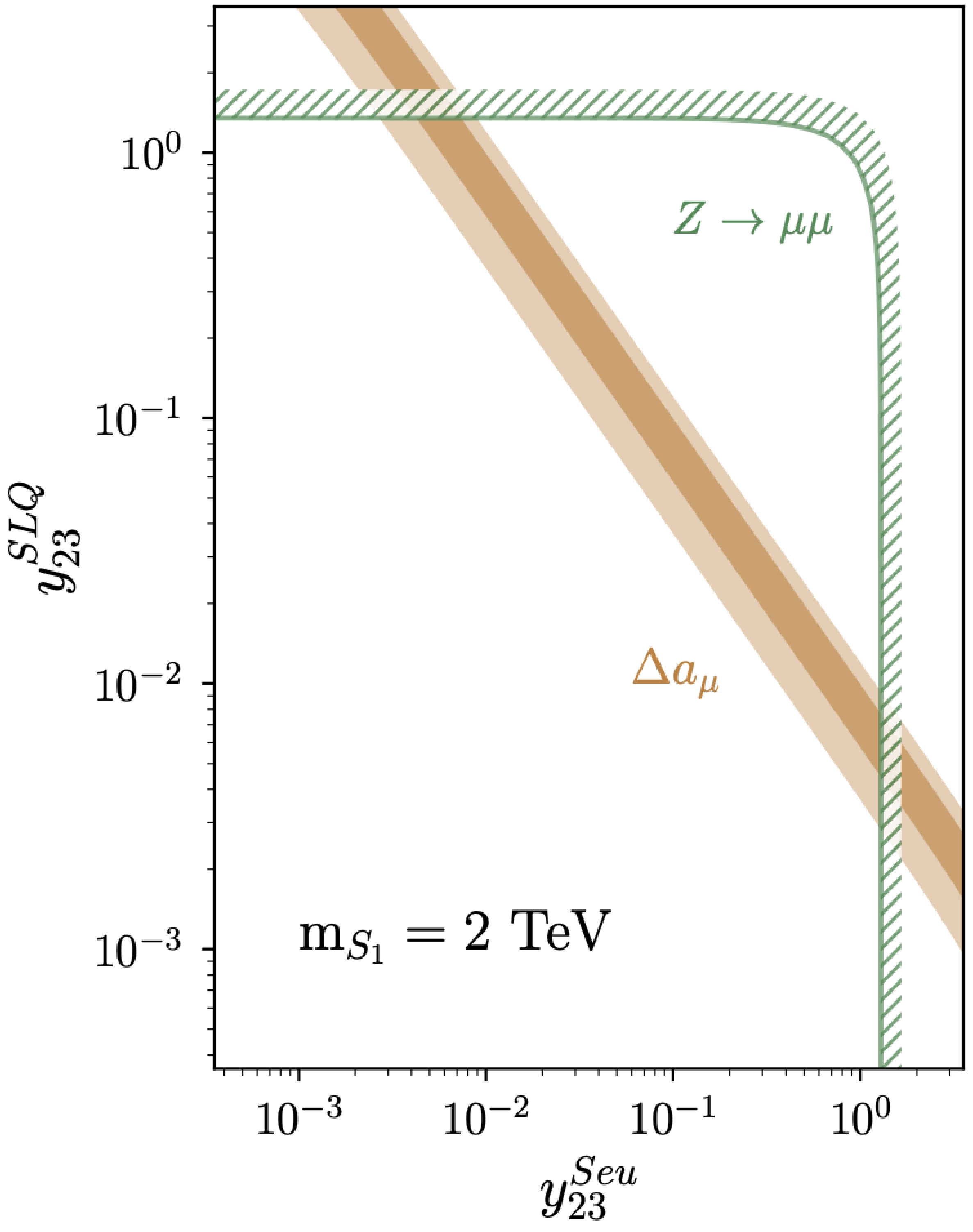
S_1 leptoquark: benchmark mass

Method 1



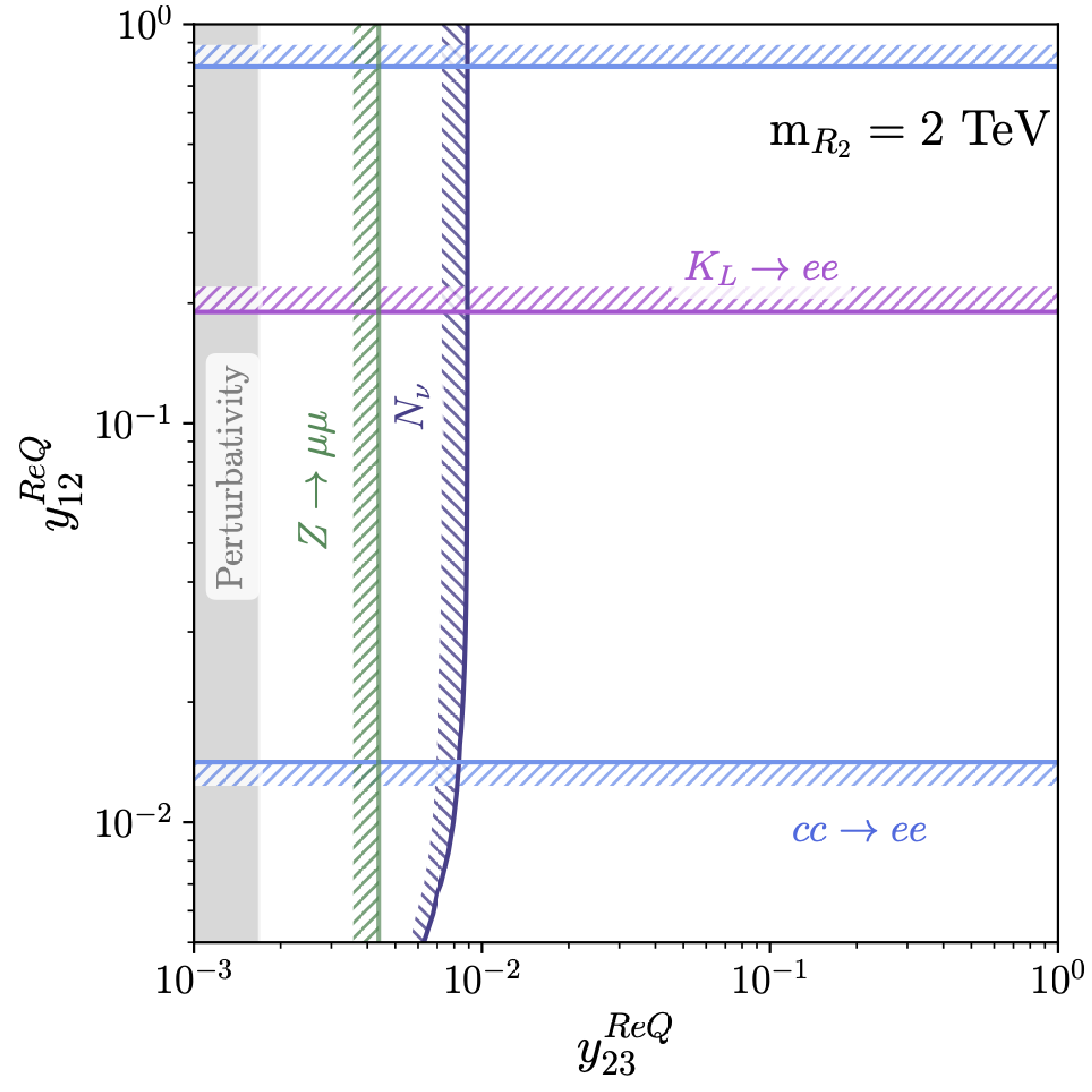


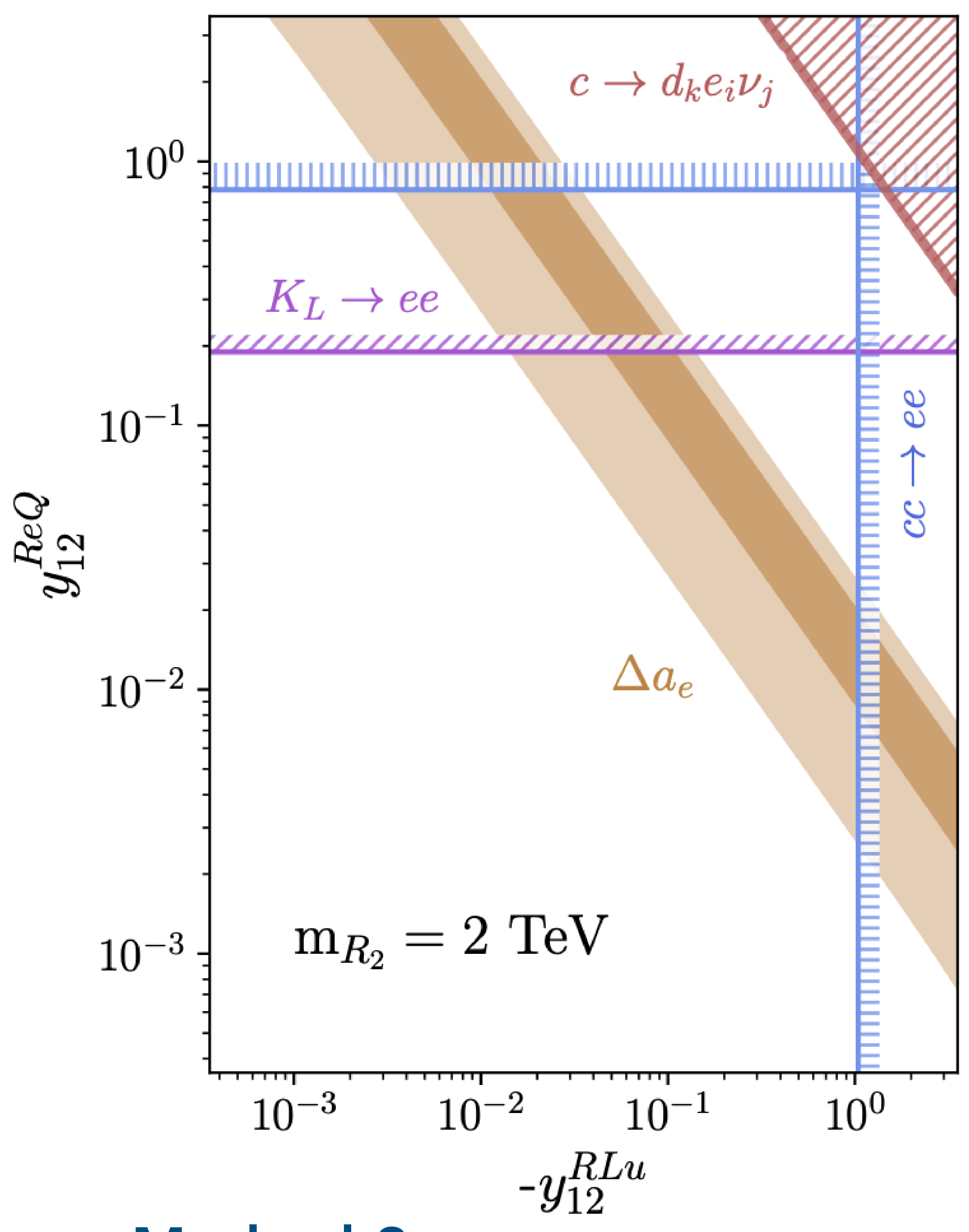
Method 2

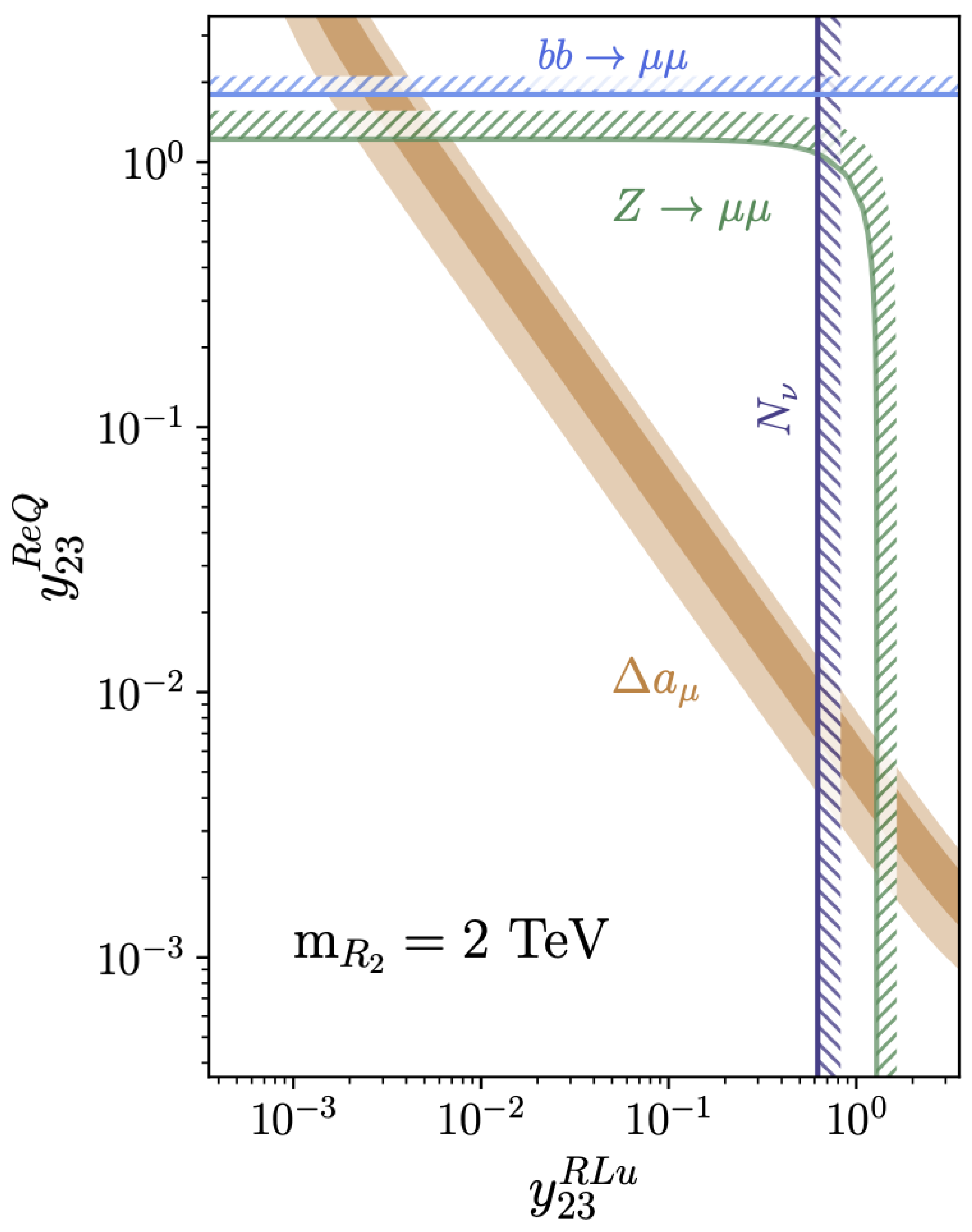


R_2 leptoquark: benchmark mass

Method 1







Method 2

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 maximally 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)