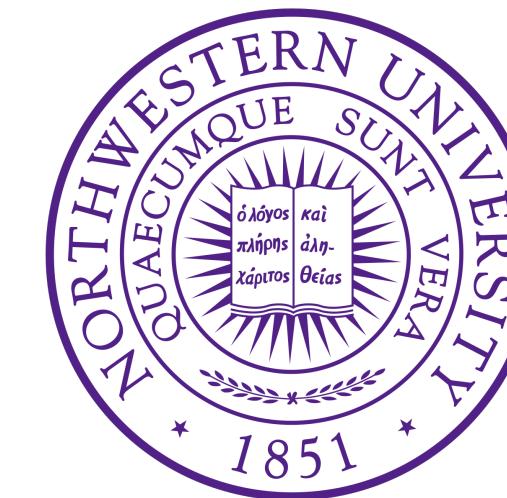


Getting Chirality Right

single scalar leptoquarks
and lepton dipole moments

Innes Bigaran

Based on **Bigaran, I.**, Volkas, R.R, arXiv: 2002.12544 and 2110.03707



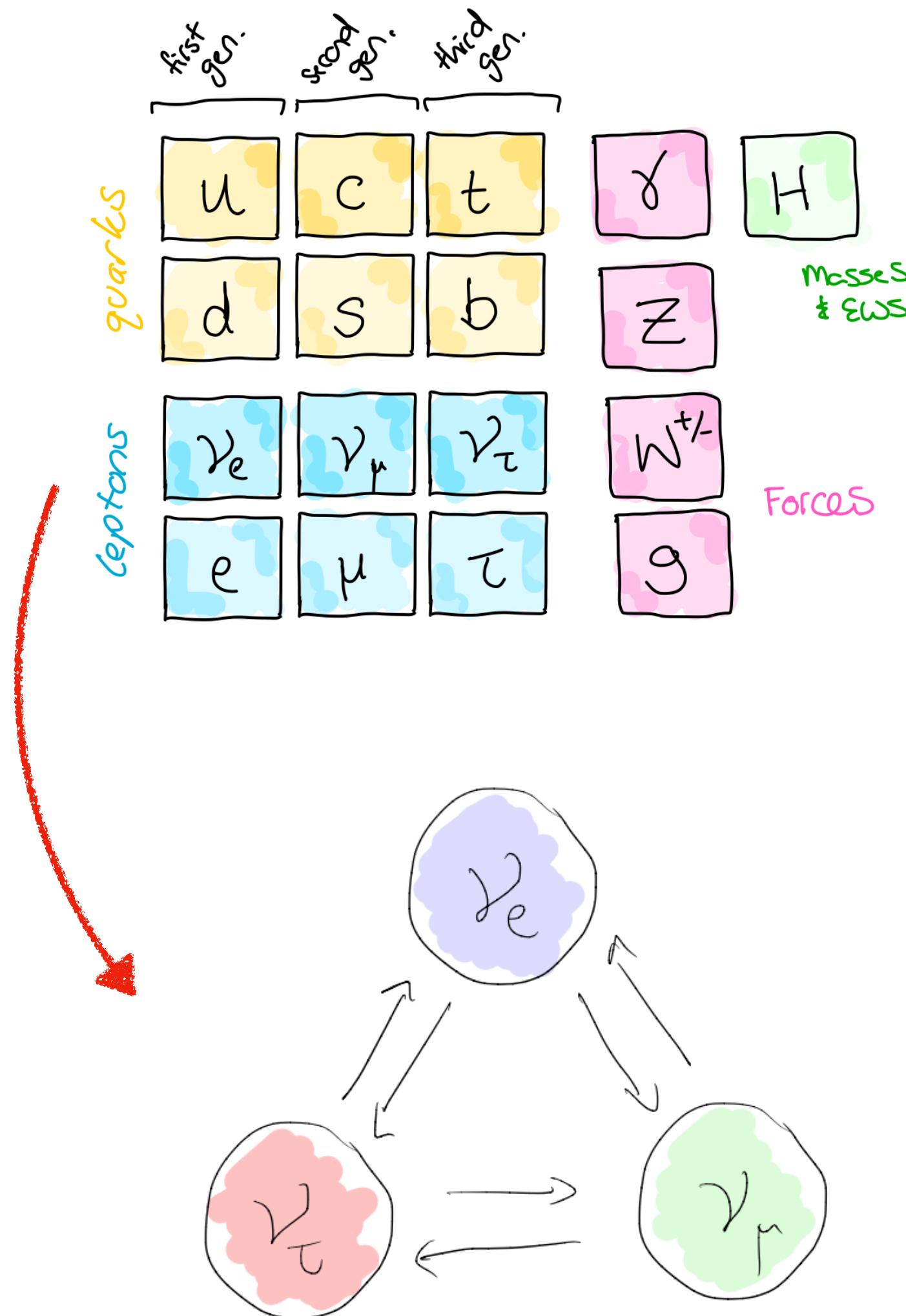
Overview

1. The problem
 2. A solution
 3. What we learn from the solution, even if anomalies “disappear”...
-

Overview

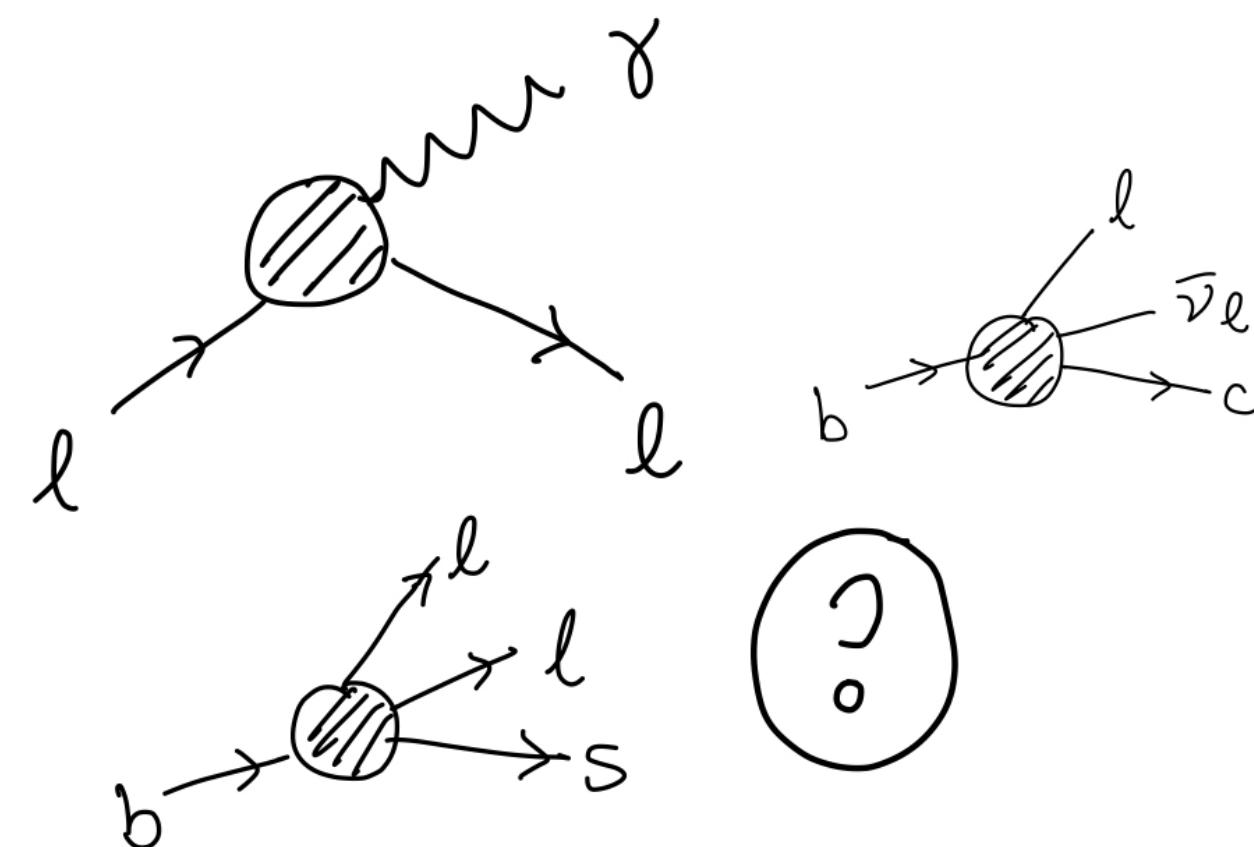
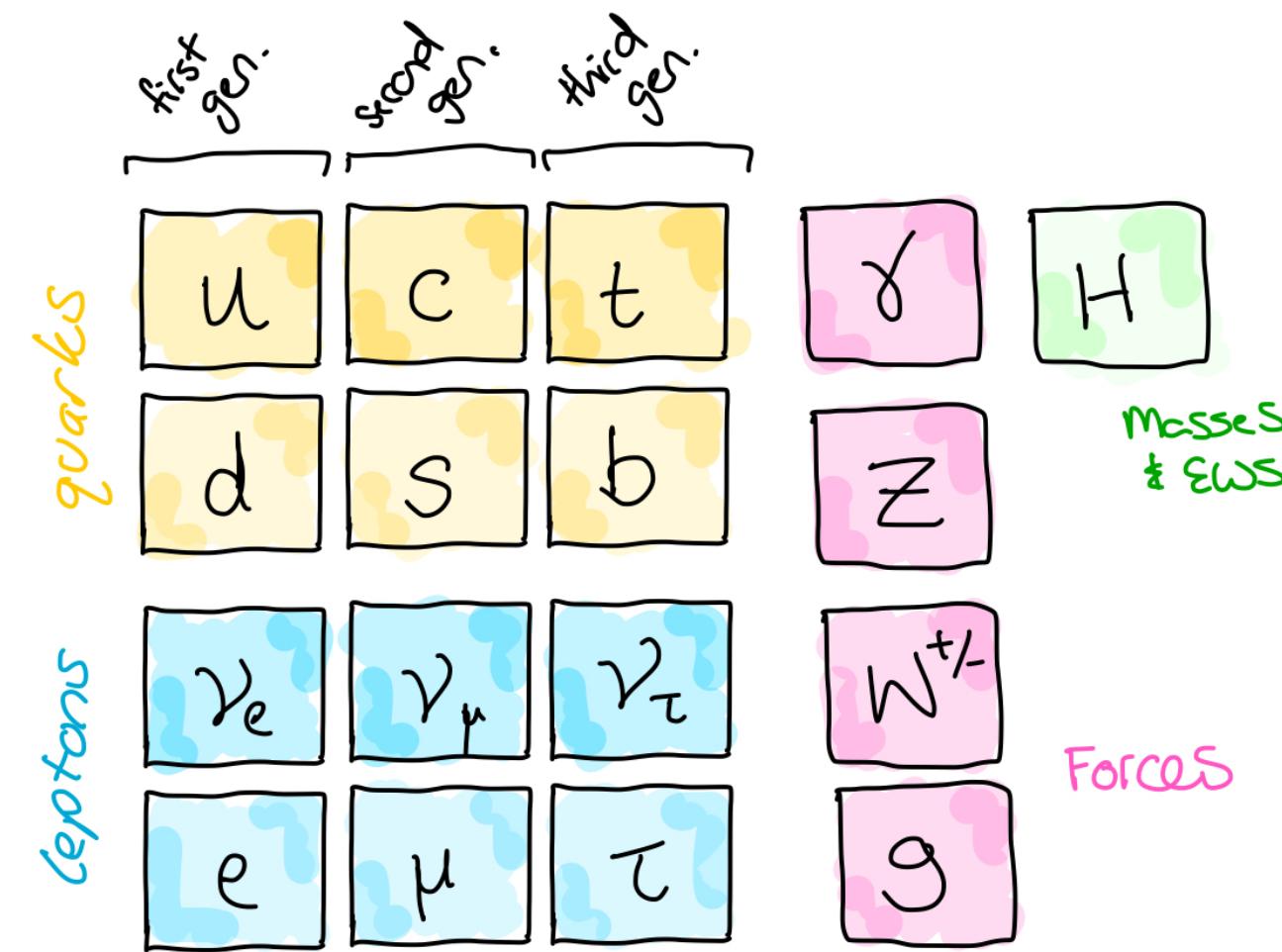
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Lepton flavour in the SM



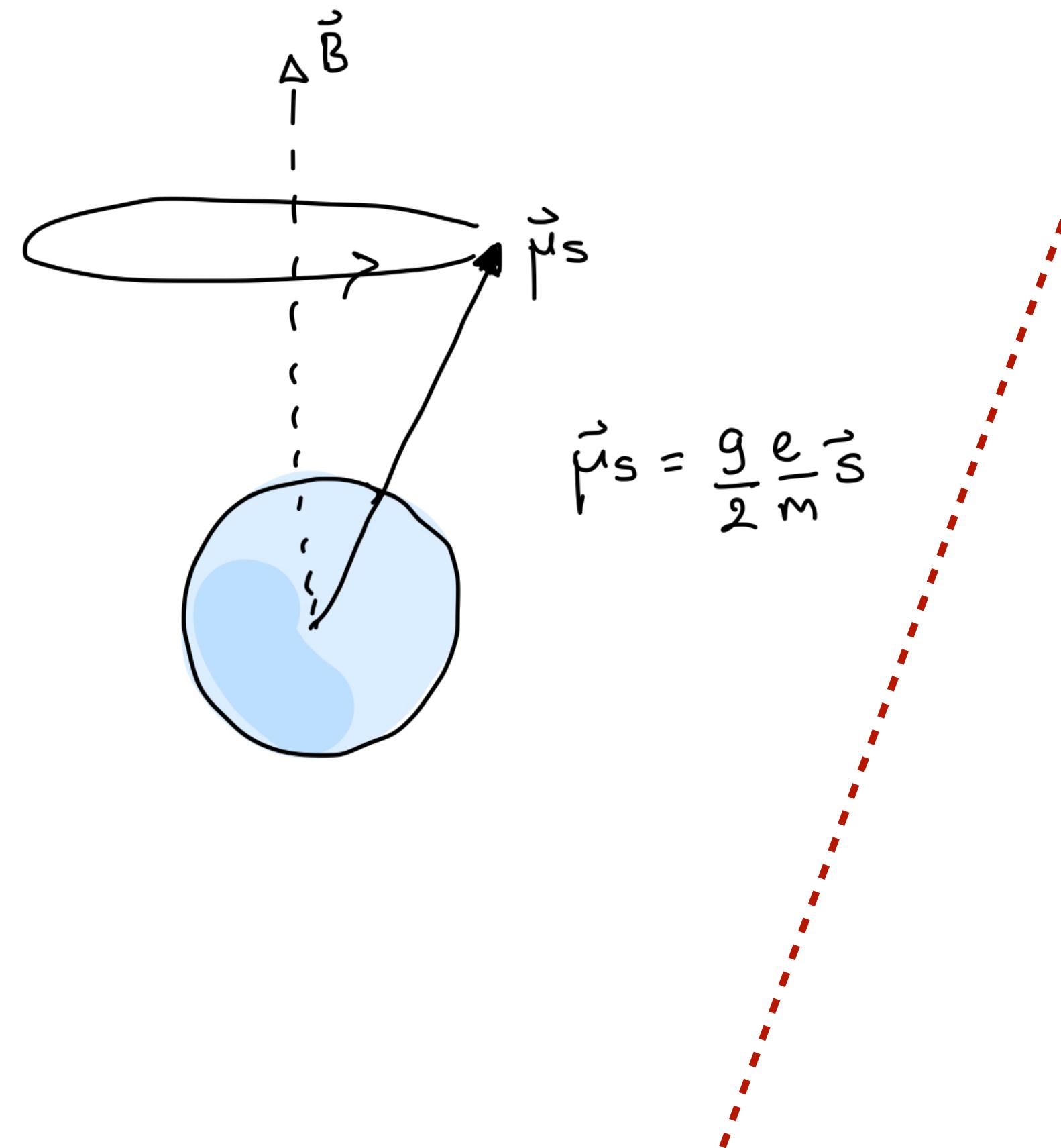
- Within the SM, neutrinos are massless.
- SM + massless neutrinos: accidental conservation of [flavoured] lepton number
- Observed neutrino oscillations mean
 - (a) massive neutrinos and;
 - (b) there is lepton flavour violation (LFV) beyond the SM

Lepton flavour in the SM



- SM leptons couple flavour-blindly to the gauge fields of the SM: **lepton flavour universality (LFU)**
- The only flavour non-universal couplings to leptons in the SM come via charged-lepton masses
- Further signs of LFU violation could be signs of new physics...

The electron g-2



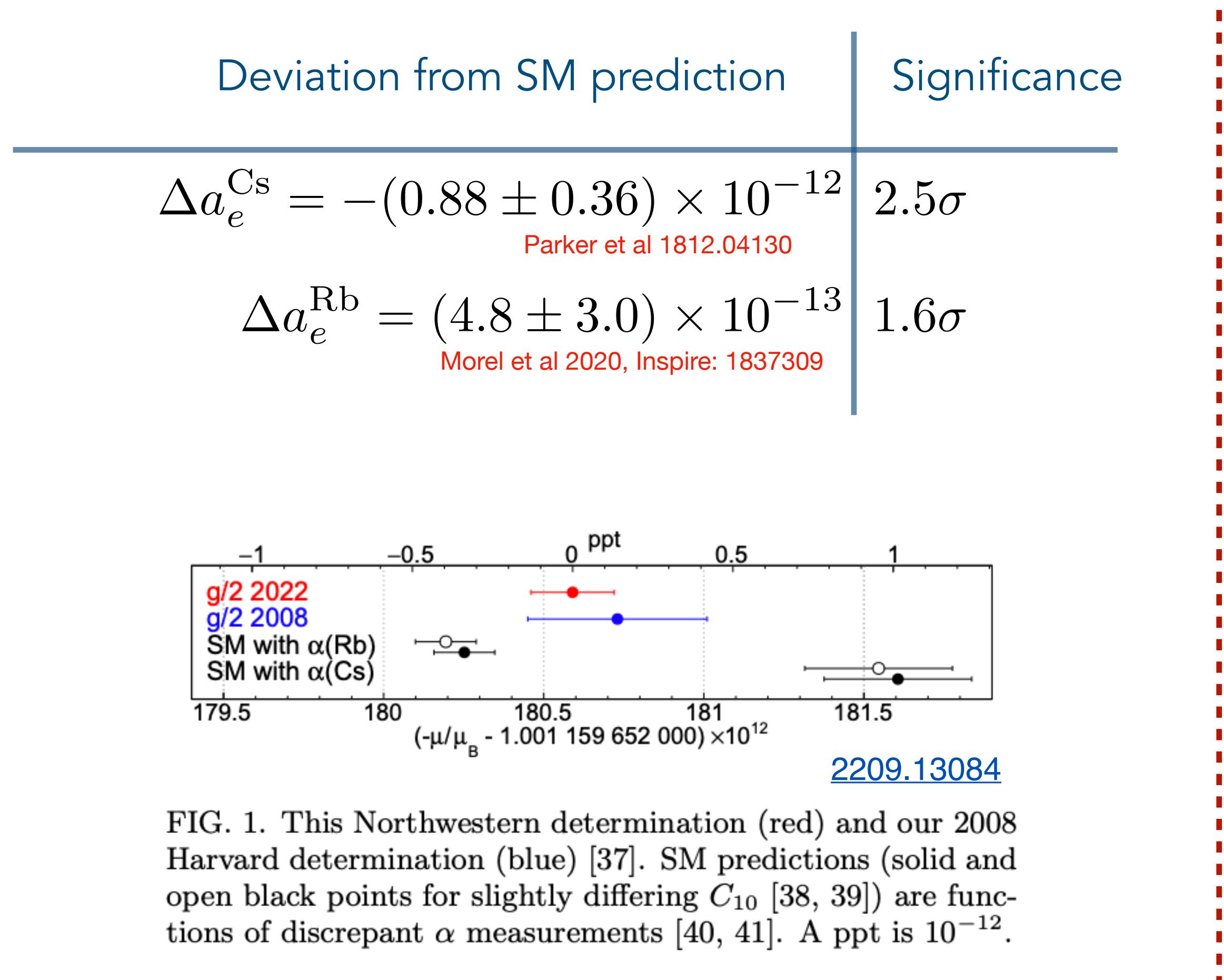
- Electron magnetic moment: long-term precision test of the SM and QED
- Anomalous magnetic moment (AMM): correction to the leading-order value ($g=2$) parameterised by $a_\ell = \frac{1}{2}(g - 2)$
- Measuring the fine-structure constant historically via

$$a_e^{\text{SM}} = a_e^{\text{SM}}(\alpha)$$

measure a_e^{Exp} → $\underbrace{a_e^{\text{Exp}} = a_e^{\text{SM}}}_{\text{(assumes no new physics!)}} \rightarrow$ derive α

- In order to relax the assumption of no BSM , require independent measurements of alpha

The electron g-2



- Measure alpha using atom interferometry and used to calculate the “SM contribution”

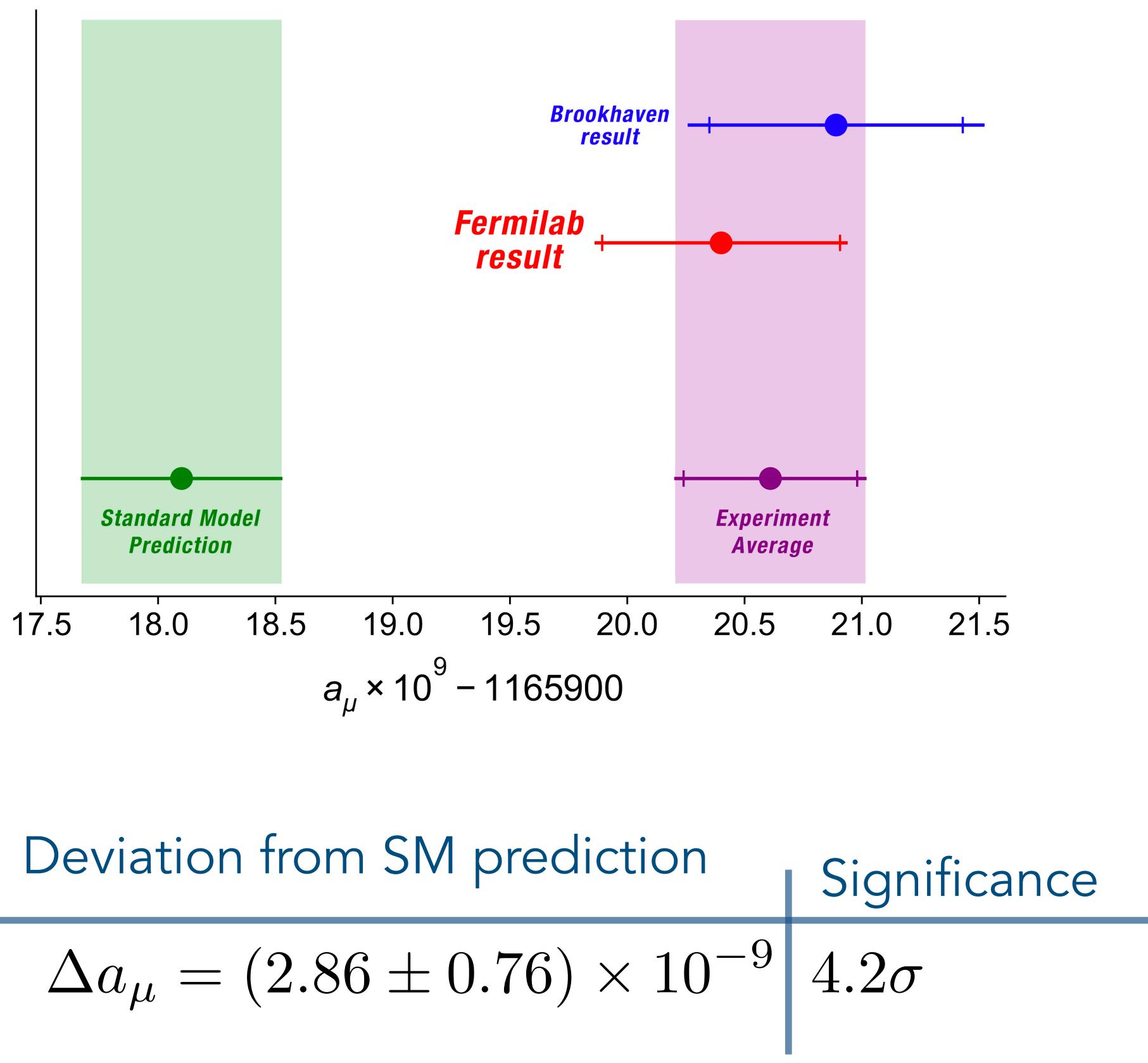
Measure α $\rightarrow a_e^{\text{SM}} = a_e^{\text{SM}}(\alpha)$ \rightarrow compare with expt.

$$\Delta a_e = a_{\text{exp}} - a_{\text{SM}}$$

- If this value is nonzero: there’s an anomaly in the electron AMM

The muon g-2

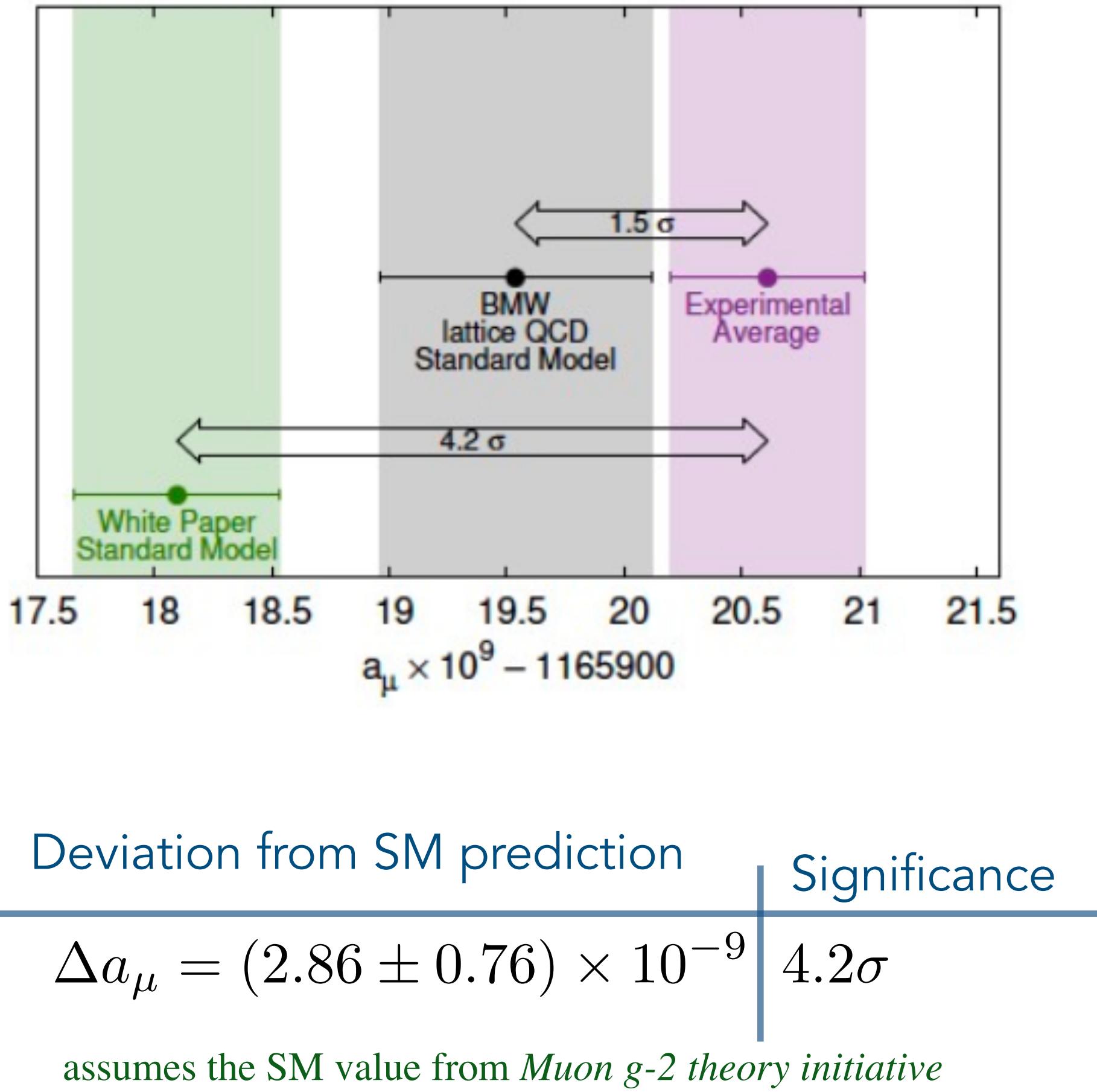
Circa 2020, FNAL announcement



- To test the muon magnetic moment, requires a larger higher-energy experiment to measure muon precession in a B field (BNL and Fermilab experiments)
- There is a long-standing anomaly in the muon g-2
- Taken together with the electron g-2, this looks a lot like new physics coupling differently to e and mu

The muon g-2

Circa 2020, later that same week...



- To test the muon magnetic moment, requires a larger higher-energy experiment to measure muon precession in a B field (BNL and Fermilab experiments)
- There is a long-standing anomaly in the muon g-2
- Taken together with the electron g-2, this looks a lot like new physics coupling differently to e and mu
- Discussion of SM contribution is beyond the scope of this talk — but very interesting!

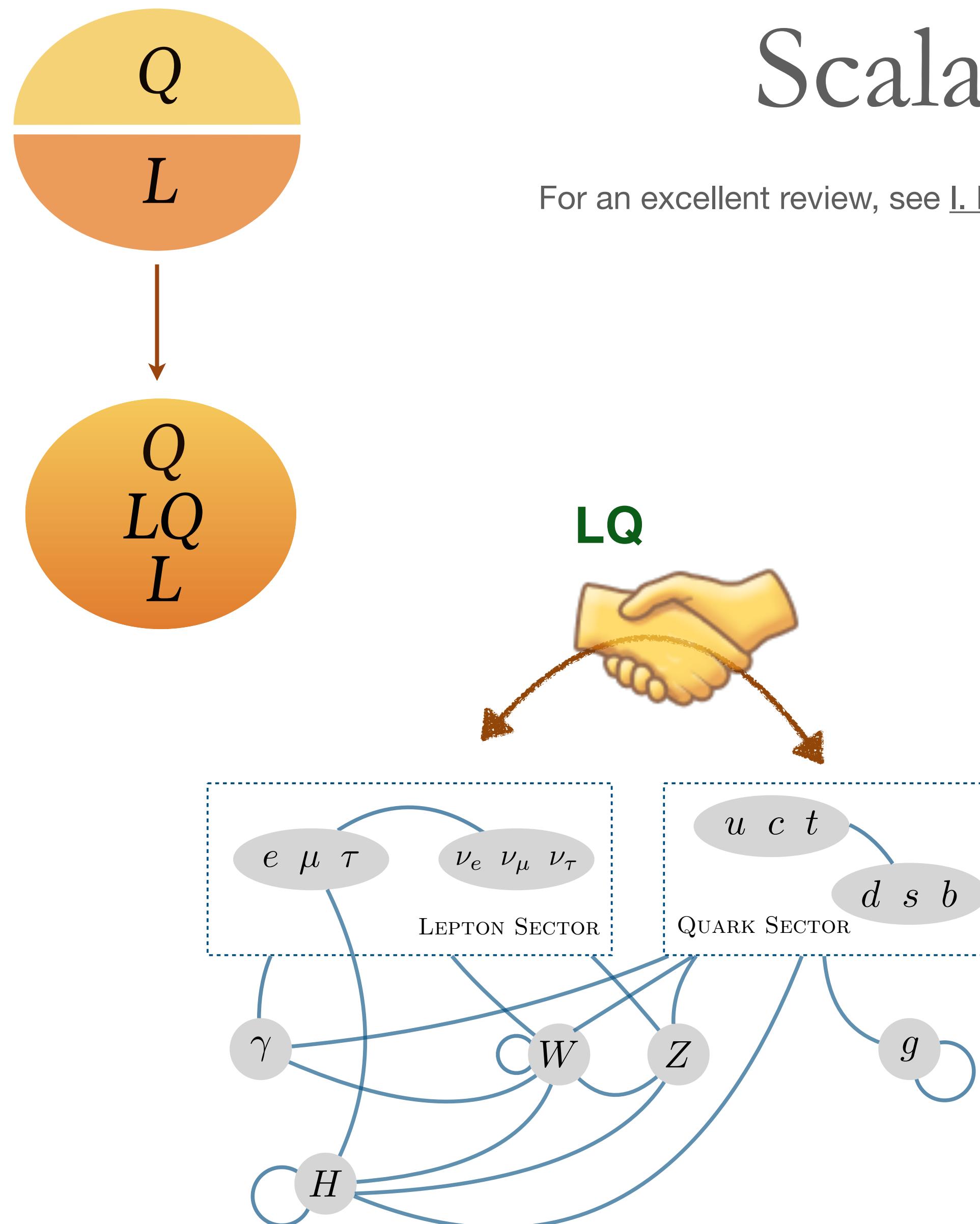
The problem: summary

- Measurements of the g-2 of the muon and the electron deviate from the SM prediction
- In 2020: deviations from the SM are in *opposite* directions for different lepton flavours
- In 2021: the deviations may be in the same *or* opposite directions
- Could new physics be coupling to the muon and electron differently?

Deviation from SM prediction	Significance
$\Delta a_\mu = (2.86 \pm 0.76) \times 10^{-9}$	4.2σ
$\Delta a_e^{\text{Cs}} = -(0.88 \pm 0.36) \times 10^{-12}$	2.5σ
$\Delta a_e^{\text{Rb}} = (4.8 \pm 3.0) \times 10^{-13}$	1.6σ

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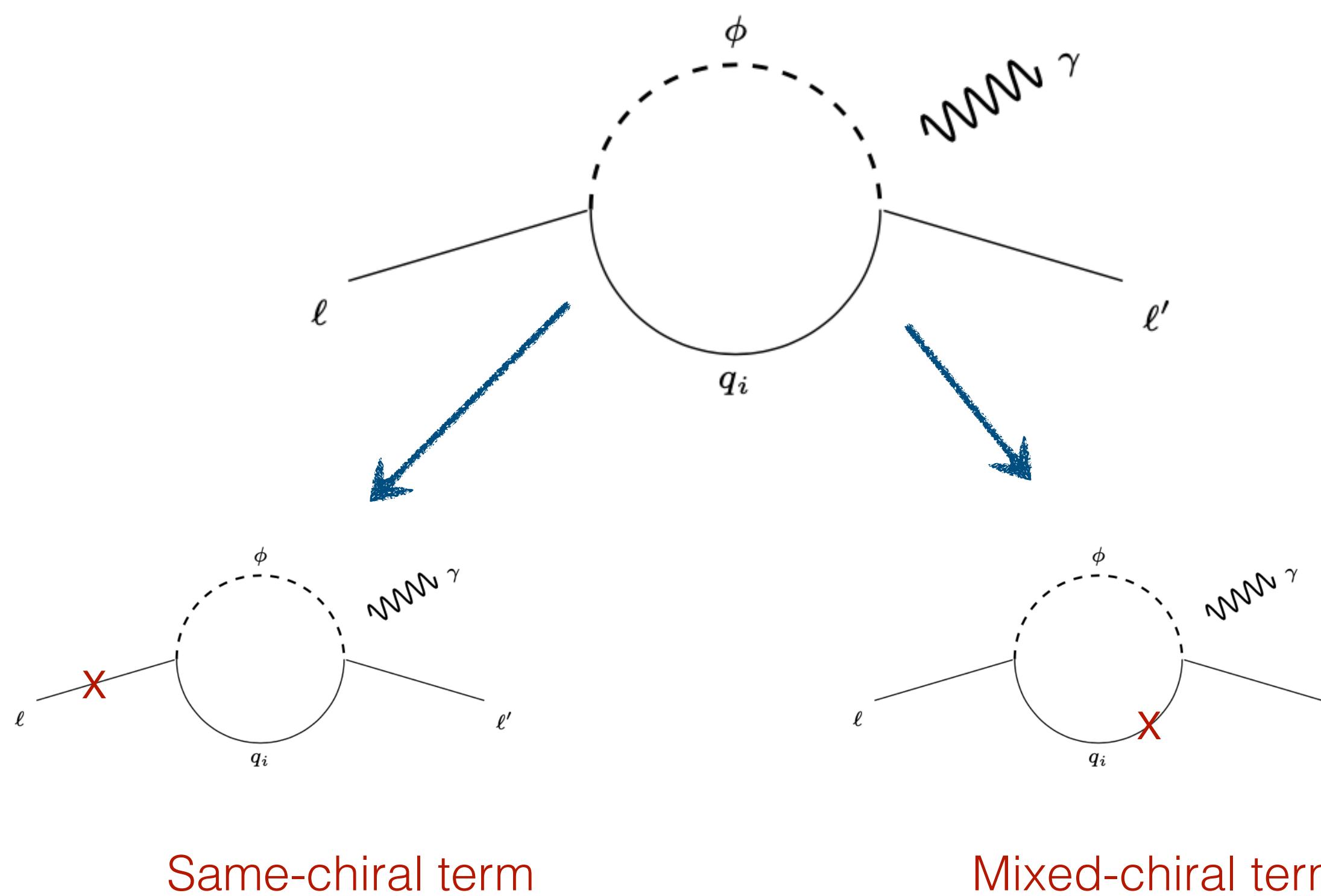


Scalar leptoquarks

For an excellent review, see [I. Doršner, S. Fajfer, A. Greljo, J. F. Kamenik, N. Košnik 1603.04993](#)

- Leptoquarks (LQ) are hypothetical particles which directly couple SM leptons and quarks
- They appear in neutrino mass models, GUT theories, flavour models...
- Scalar LQ are simple extensions to the SM
- LQ masses and couplings between are generally extra free parameters, but can be understood as arising from larger ‘model-space’
- Easily lead to LFU violation

Scalar leptoquarks



- General coupling of the scalar LQ to charged leptons

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

coupling to LH q
Coupling to RH q

← Leptoquark

- Contribution to the AMM of a lepton

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

Same-chiral term
Mixed-Chiral term

Scalar leptoquarks

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

$$\left. + m_q \text{Re}(y_\ell^{L*} y_\ell^R) \kappa' \right]$$

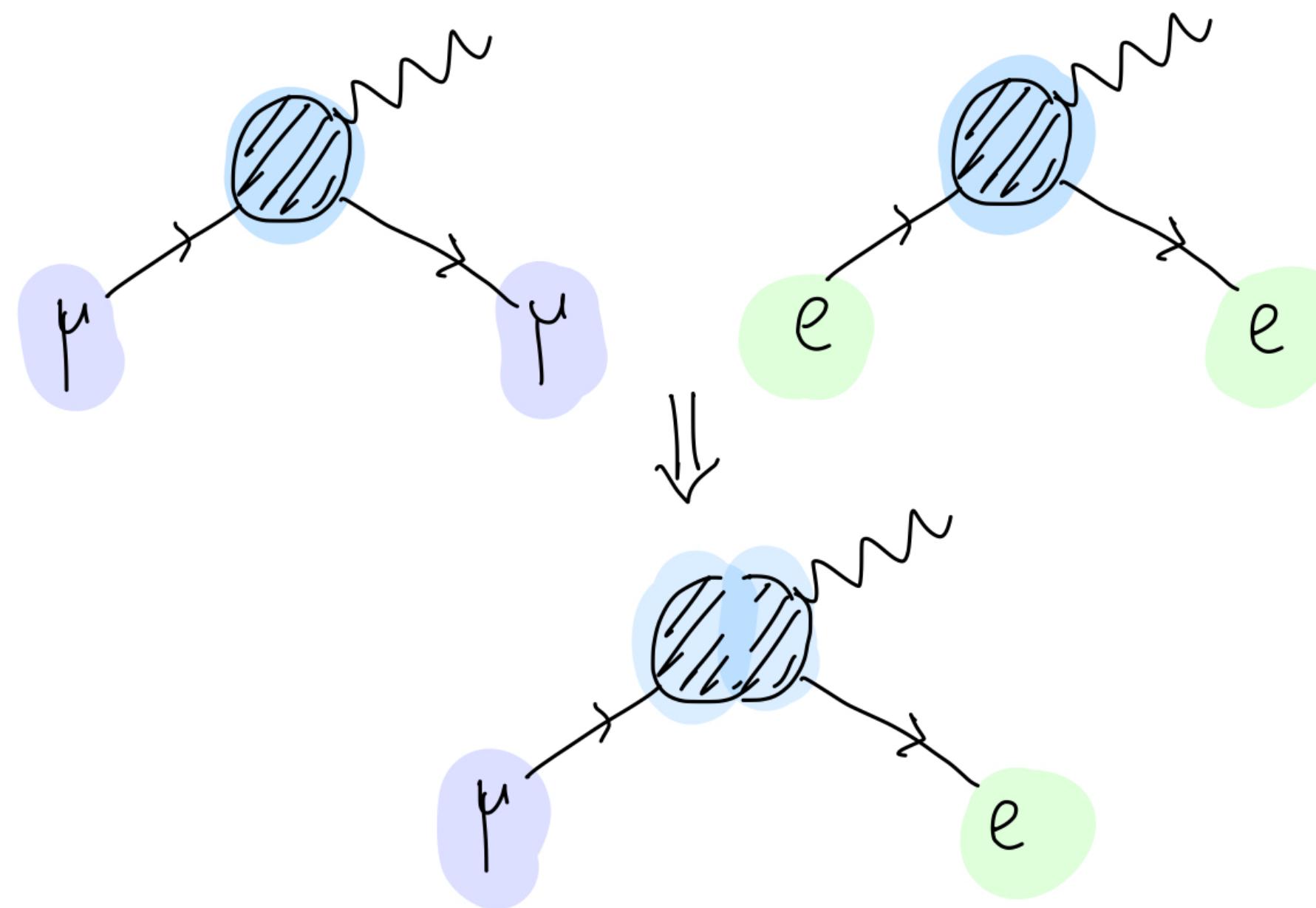
Mixed-Chiral term

Deviation from SM prediction	Significance
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- Flavoured sign-dependence of the correction must come from the mixed-chiral term (loop functions have no lepton flavour structure)
- If pulls from the SM are in opposite directions, scalar LQ that generate both anomalies must be mixed-chiral
- Mixed-chiral correction may also be enhanced by quark mass

A no-go theorem for $(g-2)_e/\mu$?

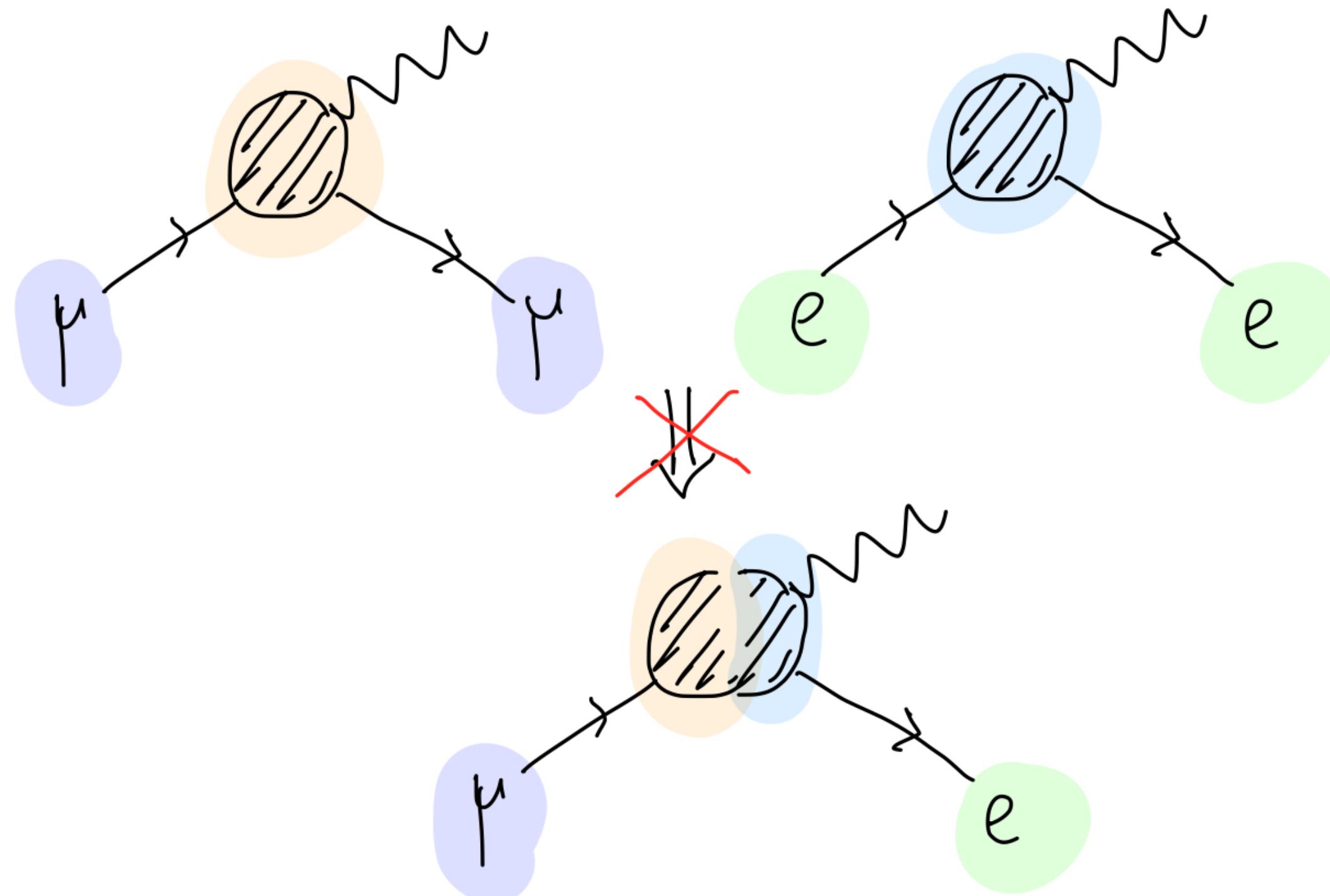
See e.g. Crivellin et al [1807.11484](#), Doršner, Fajfer, Saad [2006.11624](#)



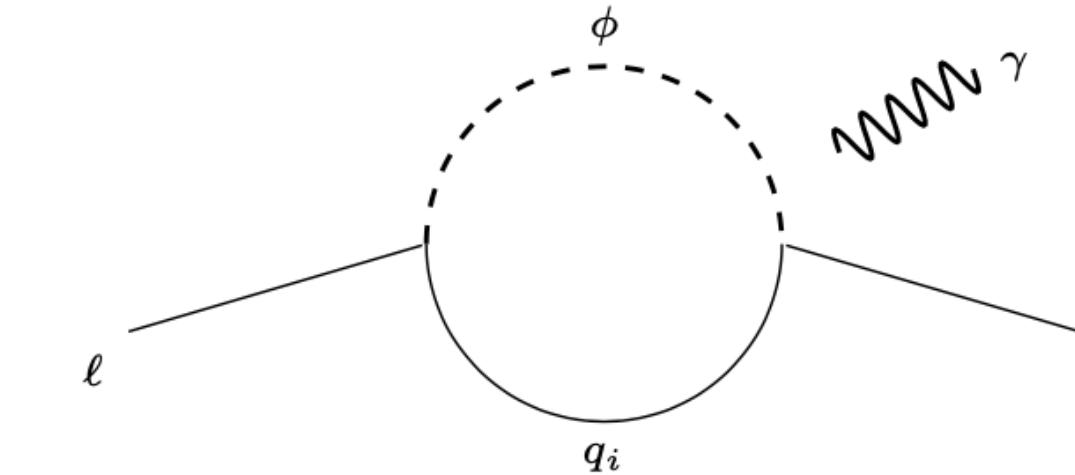
- Rather large contributions to the anomalous magnetic moment of both leptons
- Quite strong constraints from charged LFV involving first and second generation leptons
- Eight orders of magnitude above the present bound

$$\text{Br}[\mu \rightarrow e\gamma] = \frac{\alpha m_\mu^2}{16m_e\Gamma_\mu} |\Delta a_\mu \Delta a_e| \sim 8 \times 10^{-5}$$

Scalar LQs for $(g-2)_e/\mu$



- However, if the intermediate particles coupling are inequivalent, we can avoid this constraint
- Couple the *same* LQ to *different* SM up-type quarks: single scalar LQs can explain both the muon and electron g-2



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	$(\mathbf{3}, \mathbf{2}, 1/6)$

Bigaran, I., Volkas, R.R, arXiv: 2002.12544

Avoiding cLFV? A lesson in bases

- Couplings between left-handed up/down type quarks and leptons are not uniquely defined.

$$\mathcal{L}_{\text{int}}^{S_1} = (\overline{L}_L^c \lambda_{LQ} Q_L + \overline{e}_R^c \lambda_{eu} u_R) S_1^\dagger + h.c.,$$



EWSB and rotating fields
into mass-eigenstates

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

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

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

‘Up-type’ $+ y_{ij}^{Seu} \overline{e}_{R,i}^c u_{R,j} S_1^\dagger + h.c.,$

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

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

‘Down-type’ $+ y_{ij}^{Seu} \overline{e}_{R,i}^c u_{R,j} S_1^\dagger + h.c.,$

Avoiding cLFV? A lesson in bases

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

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

'Up-type'

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

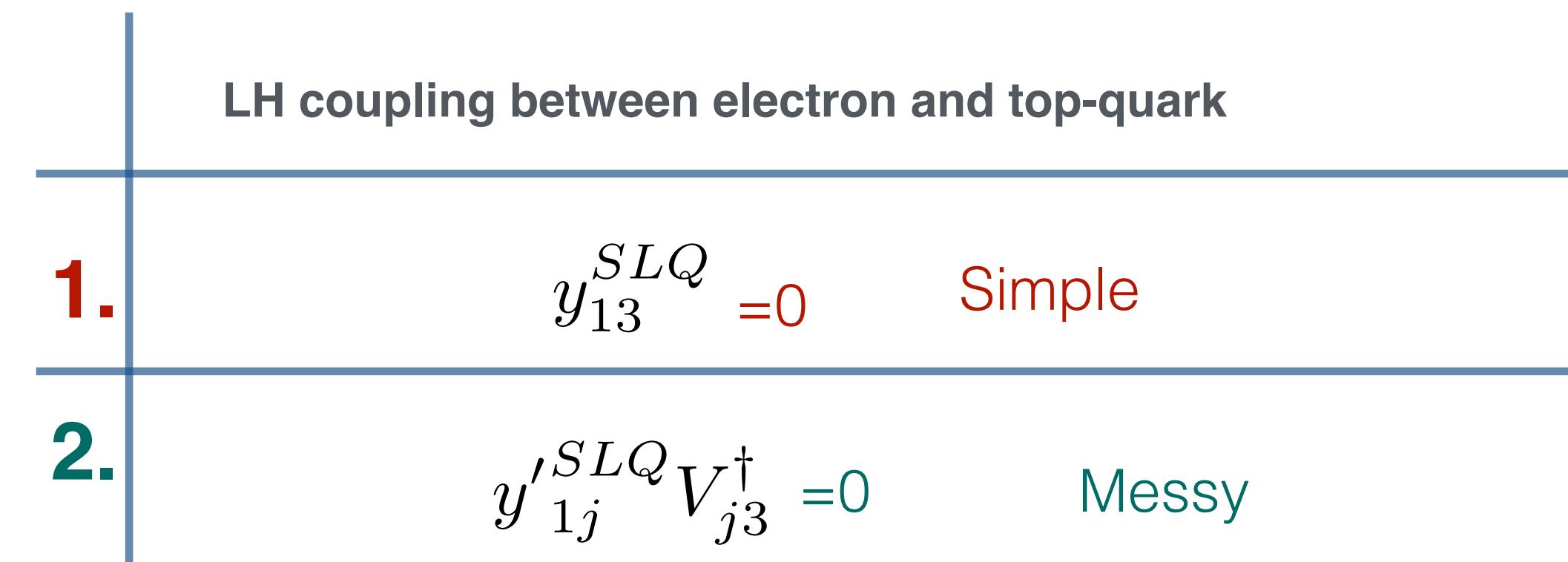
2. $\mathfrak{R}_e \lambda_{eu} \mathfrak{R}_u \mapsto y^{Seu}$, $\mathfrak{L}_e \lambda_{LQ} \mathfrak{L}_d \mapsto y'^{SLQ}$,

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

'Down-type'

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

- If we choose a down-type basis, it would be very hard to avoid large (top-mass enhanced) corrections to cLFV *and* generate both g-2's
- Note that only couplings to up-type quarks with charged leptons here are mixed-chiral



Scalar LQs for (g-2)_{e/mu}

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

u	c	t
$y^L \sim \begin{pmatrix} 0 & \text{■} & 0 \\ 0 & 0 & \text{■} \\ 0 & 0 & 0 \end{pmatrix},$	$y^R \sim \begin{pmatrix} 0 & \text{■} & 0 \\ 0 & 0 & \text{■} \\ 0 & 0 & 0 \end{pmatrix}$	e μ τ

A Feynman diagram illustrating a loop correction. A dashed circle labeled ϕ represents a scalar field. Inside this loop, there is a solid circle representing a fermion loop involving quarks q_i and q_j . Two external fermion lines, labeled ℓ and ℓ' , enter and exit the loop from the left and right respectively. A wavy line labeled γ represents a photon, which is emitted from the loop.

- Contribution to g-2 of the electron via a charm quark coupling
- Contribution to g-2 of the muon via a top quark coupling
- Four new couplings, one new mass in each model

Model 1

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

Model 2

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

Full phenomenology study in 2002.12544 (real) and 2110.03707 (complex, also EDMs)

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-

What have we learned



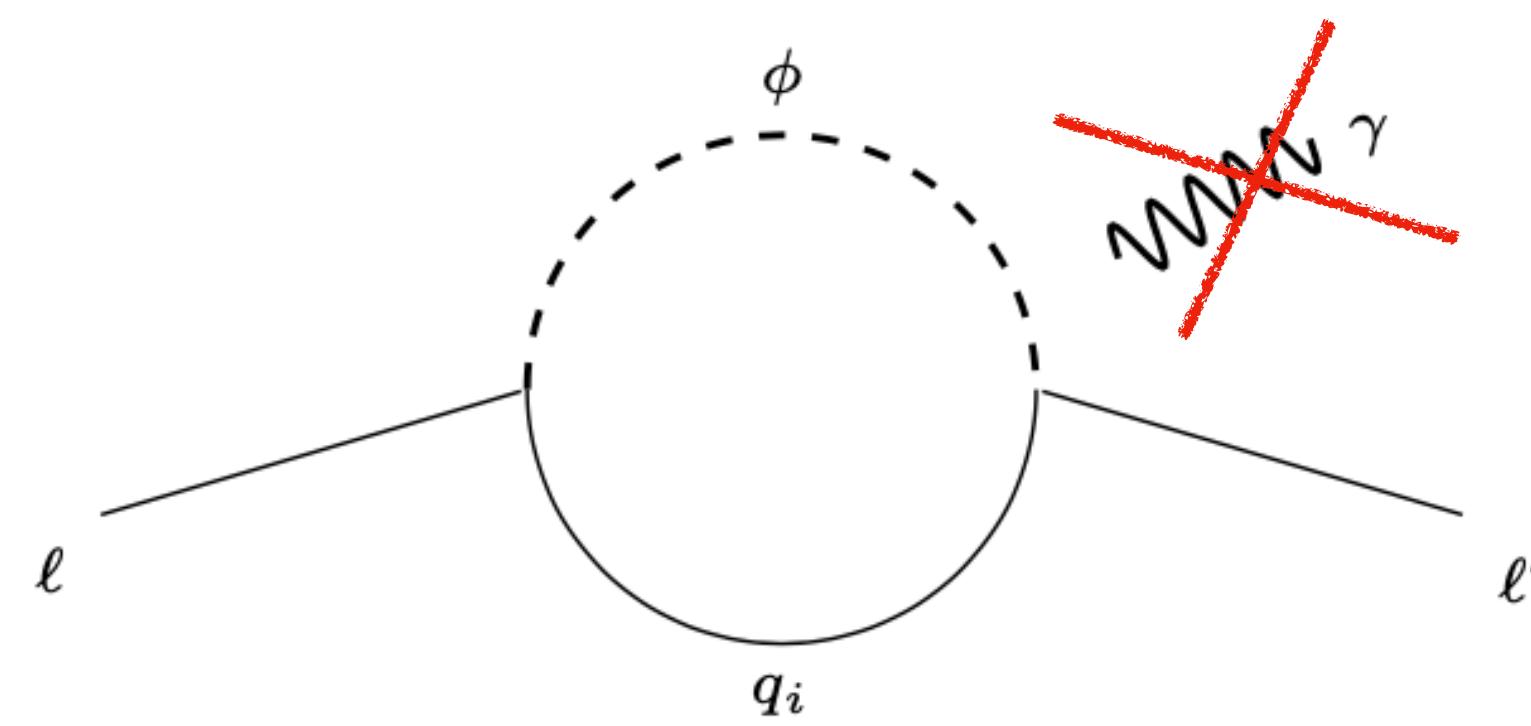
- Anomalies come and go, and some stay longer than others. Some stay forever and are no longer called “new physics” ... (neutrino masses?)
- The work done to model-build for these anomalies tells us important lessons about the structure of BSM models
- Many of these models have multiple purposes: pheno studies tell us where effects of these models can appear in various low- and high-energy probes
- We need lepton flavour violation beyond the SM!

Thank you for listening

See [2002.12544](#) and [2110.03707](#) for further details

Backup Slides

The lepton g-2 problem with mixed-chiral scalars



$$\Delta m \simeq \frac{m_q N_c}{16\pi^2} |y_{\ell q}^{R*} y_{\ell q}^L| \left[1 + \frac{2m_q^2}{m_\phi^2} \log \left(\frac{m_q}{m_\phi} \right) \right].$$

- But: consider also the (dirac) lepton masses and how this is modified by chirally-enhanced one-loop corrections.
- The self-energies could account for the masses, but shouldn't warrant overly correcting the “tree-level” terms

We enforce that the modification to the lepton (electron or muon) mass cannot be greater than 100%

$$\frac{\Delta m}{m_{\text{Tree}}} \leq 1$$

PROCESS	OBSERVABLE	CONSTRAINT
$Z \rightarrow \ell_i \ell_j$	$g_A^e/g_A^{e,\text{SM}}$	0.999681 ± 0.000698227
	$g_A^\mu/g_A^{\mu,\text{SM}}$	0.99986 ± 0.00107726
$Z \rightarrow \nu\nu$	$N_\nu^{\text{Eff.}}$	$2.9840(82)$
$K^+ \rightarrow \pi^+ \nu\nu$	Br	$(1.7 \pm 1.1) \times 10^{-10}$
$K_L^0 \rightarrow \pi^0 \nu\nu$	Br	$< 2.6 \times 10^{-8}$
$K_L^0 \rightarrow e^+ e^-$	Br	$(9_{-4}^{+6}) \times 10^{-12}$
$K_L^0 \rightarrow \mu^+ \mu^-$	Br	$(6.84 \pm 0.11) \times 10^{-9}$
$K_L^0 \rightarrow \mu^+ e^-$	Br	$< 4.7 \times 10^{-12}$
K_0 - $\overline{K_0}$ mixing	$ \epsilon_K $	$(2.228 \pm 0.011) \times 10^{-3}$
	ΔM_K	$(3.484 \pm 0.006) \times 10^{-12}$
$pp \rightarrow \ell\ell$ [68]	$ y_{12}^{Seu} $	$< 0.648 \hat{m}_\phi$
	$ y_{12}^{RLu} $	$< 0.524 \hat{m}_\phi$

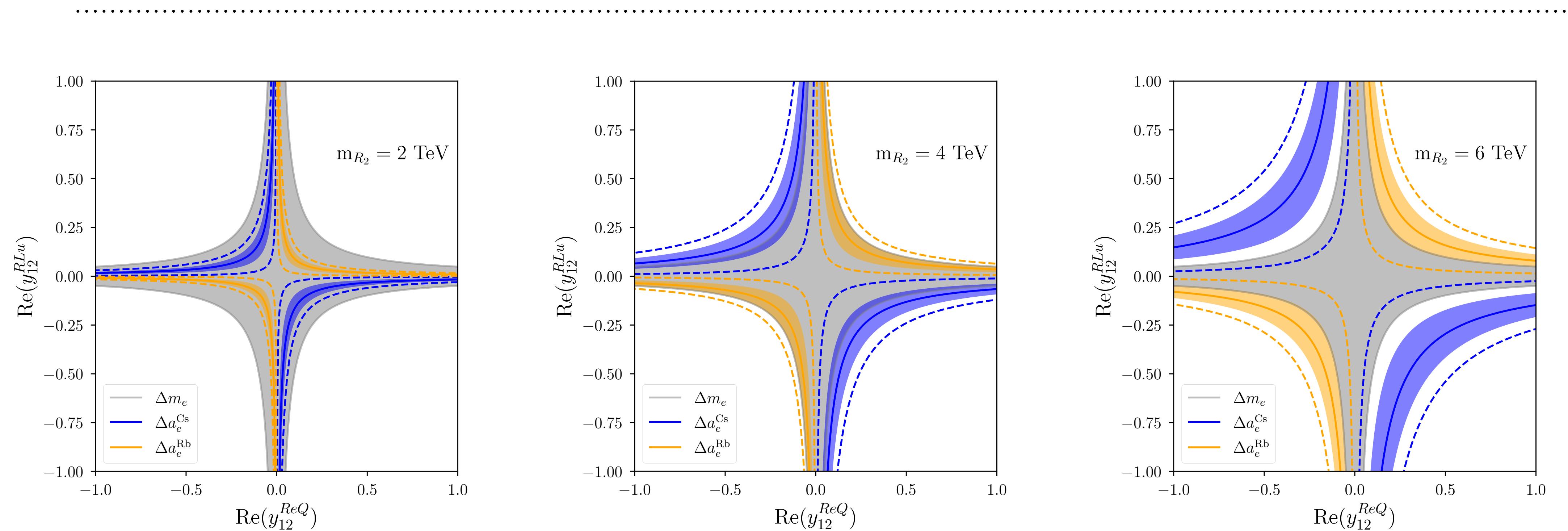
TABLE III. Processes most constraining on this model. Values quoted without citation are from PDG [69]. Constraints from $pp \rightarrow \ell\ell$ are derived from Table 1 of reference [68].

Leptoquark	Couplings	Approx. range $\times (\hat{m}_\phi^2)$
S_1	$\text{Re}[y_{23}^{L,*} y_{23}^R]$	$(3.1 \pm 0.7) \times 10^{-3}$
	$\text{Re}[y_{12}^{L,*} y_{12}^R]_{\text{Cs}}$	$-(4.6 \pm 1.9) \times 10^{-3}$
	$\text{Re}[y_{12}^{L,*} y_{12}^R]_{\text{Rb}}$	$(2.5 \pm 1.0) \times 10^{-3}$
R_2	$\text{Re}[y_{23}^{L,*} y_{23}^R]$	$-(1.8 \pm 0.4) \times 10^{-3}$
	$\text{Re}[y_{12}^{L,*} y_{12}^R]_{\text{Cs}}$	$(4.1 \pm 1.7) \times 10^{-3}$
	$\text{Re}[y_{12}^{L,*} y_{12}^R]_{\text{Rb}}$	$-(2.2 \pm 0.9) \times 10^{-3}$
Leptoquark	Couplings	Upper bound $\times (\hat{m}_\phi^2)$
S_1	$ \text{Im}[y_{23}^{L,*} y_{23}^R] $	< 1.7
	$ \text{Im}[y_{12}^{L,*} y_{12}^R] $	$< 6.2 \times 10^{-9}$
R_2	$ \text{Im}[y_{23}^{L,*} y_{23}^R] $	< 1.1
	$ \text{Im}[y_{12}^{L,*} y_{12}^R] $	$< 5.6 \times 10^{-9}$

TABLE II. Approximate one-sigma allowed ranges for the combination of couplings in the chirally-enhanced contribution to leptonic MDMs, and upper bounds for combinations of LQ couplings for contributions to leptonic EDMs. The Cs and Rb fine-structure constant implications for a_e are treated separately.

Electron g-2 with mixed-chiral scalars

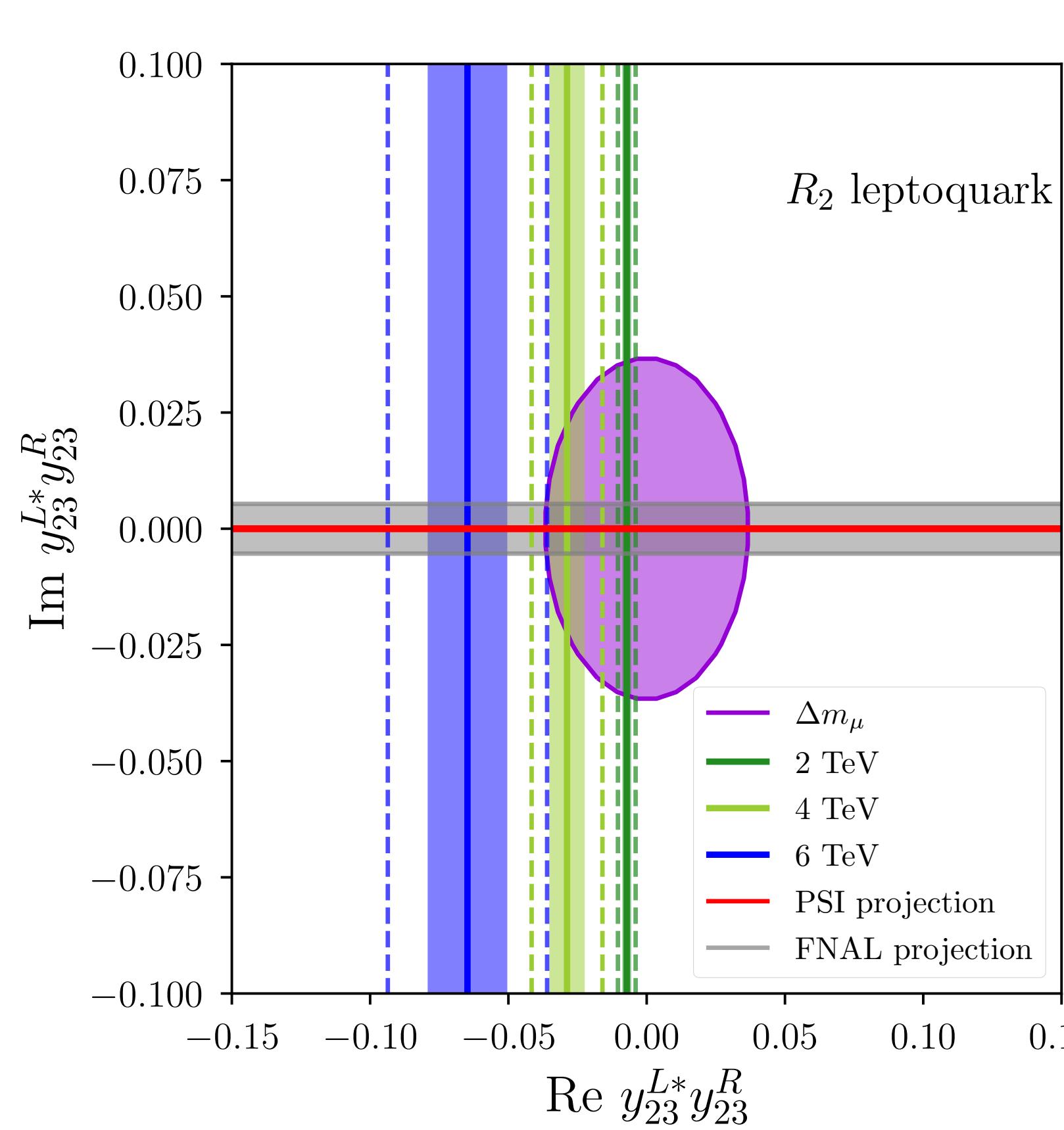
Constraint on the LQ mass from electron g-2 and correction to electron mass $m_\phi \lesssim 3.12$ TeV



Plots shown as e.g. for R2

Muon g-2 with mixed-chiral scalars

- We allow muon couplings to be complex, muon EDM is not yet highly constrained (current constraint not visible on plot, $< 10^{-19}$ e.cm)



$$\Delta a_{e_i} \propto \text{Re}(y_{ij}^{L*}y_{ij}^R)$$

$$d_{e_i} \propto \text{Im}(y_{ij}^{L*}y_{ij}^R)$$

- By looking at *just* the combination of $g-2$ (central value) with the muon mass correction constraint:

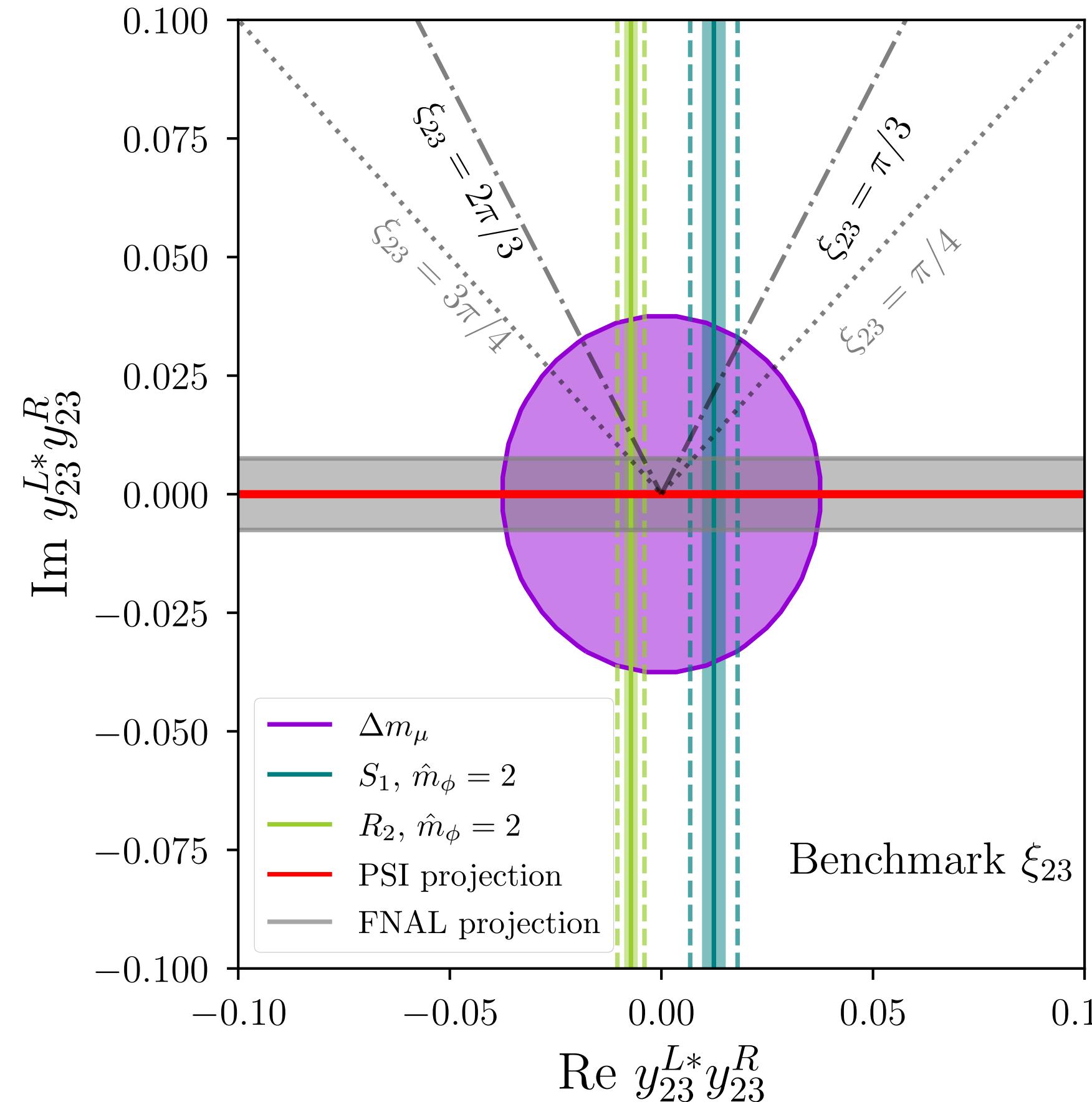
$$m_{S_1}/\text{TeV} \lesssim \begin{cases} 4.08, & \text{at CV} \\ 4.71, & \text{at } 1\sigma \\ 4.85, & \text{at } 2\sigma \end{cases}, \quad m_{R_2}/\text{TeV} \lesssim \begin{cases} 3.59, & \text{at CV} \\ 5.36, & \text{at } 1\sigma \\ 6.32, & \text{at } 2\sigma \end{cases}.$$

** Note for the plot: shaded bands in y show the region which would be still *not* observable at the respective experiment

Plot shown as e.g. for R2

Muon g-2 with mixed-chiral scalars

$$\xi_{ij} = \text{Arg}(y_{ij}^R) - \text{Arg}(y_{ij}^L)$$



- Benchmark values of ξ_{23} : capable of satisfying the g-2 value for either R_2 or S_1
- For benchmark masses, combining the muon mass with g-2 leads to a prediction for muon EDM —within reach of upcoming experiments

$$|d_\mu|_{R_2} \lesssim \left\{ \begin{array}{ll} 3.91, & \hat{m}_\phi = 2 \\ 1.25, & \hat{m}_\phi = 4 \\ 0.62, & \hat{m}_\phi = 6 \end{array} \right\} \times 10^{-22} \text{ e cm.}$$

$$|d_\mu|_{S_1} \lesssim \left\{ \begin{array}{ll} 2.77, & \hat{m}_\phi = 2 \\ 0.96, & \hat{m}_\phi = 4 \\ 0.50, & \hat{m}_\phi = 6 \end{array} \right\} \times 10^{-22} \text{ e cm};$$

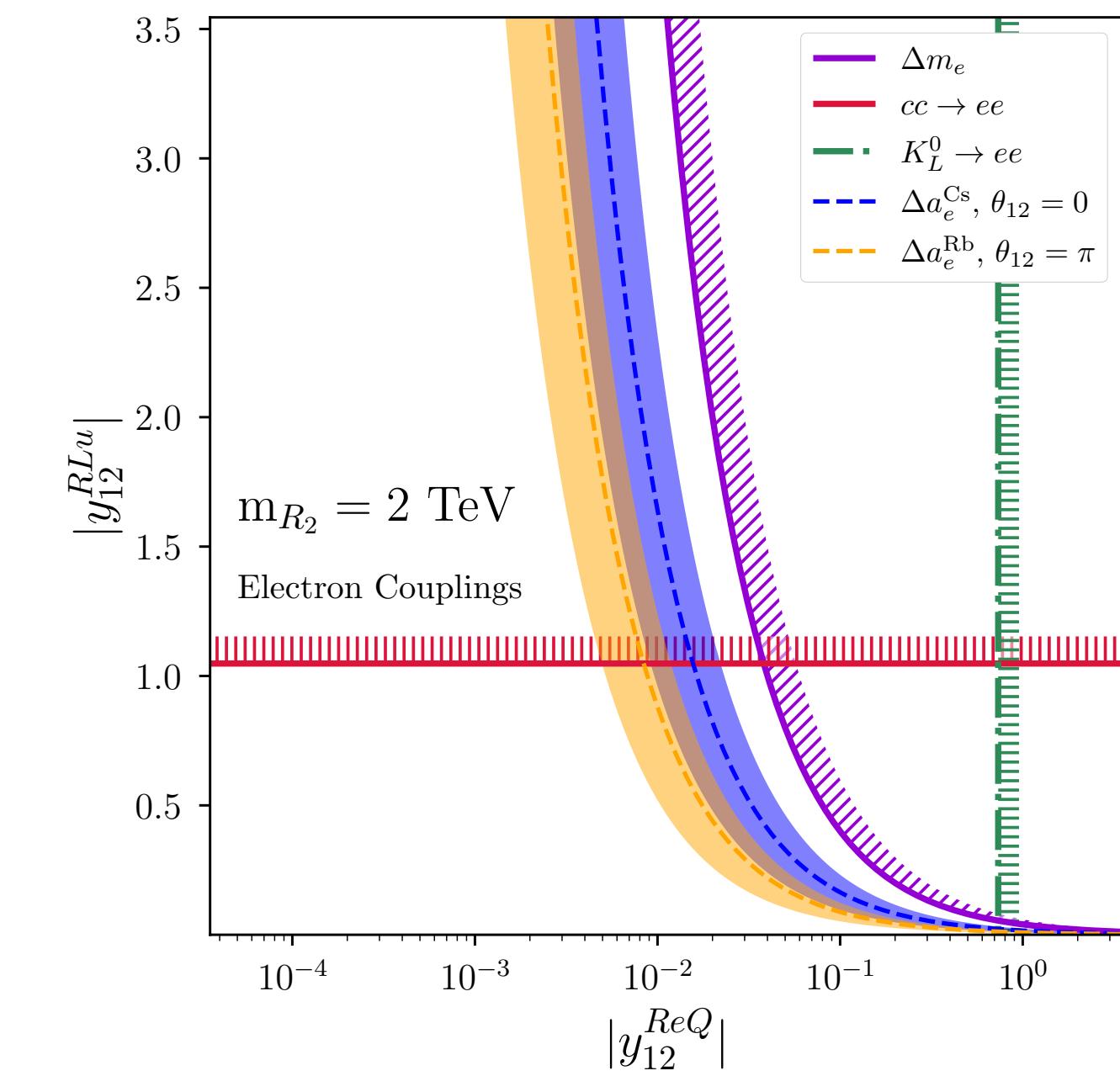
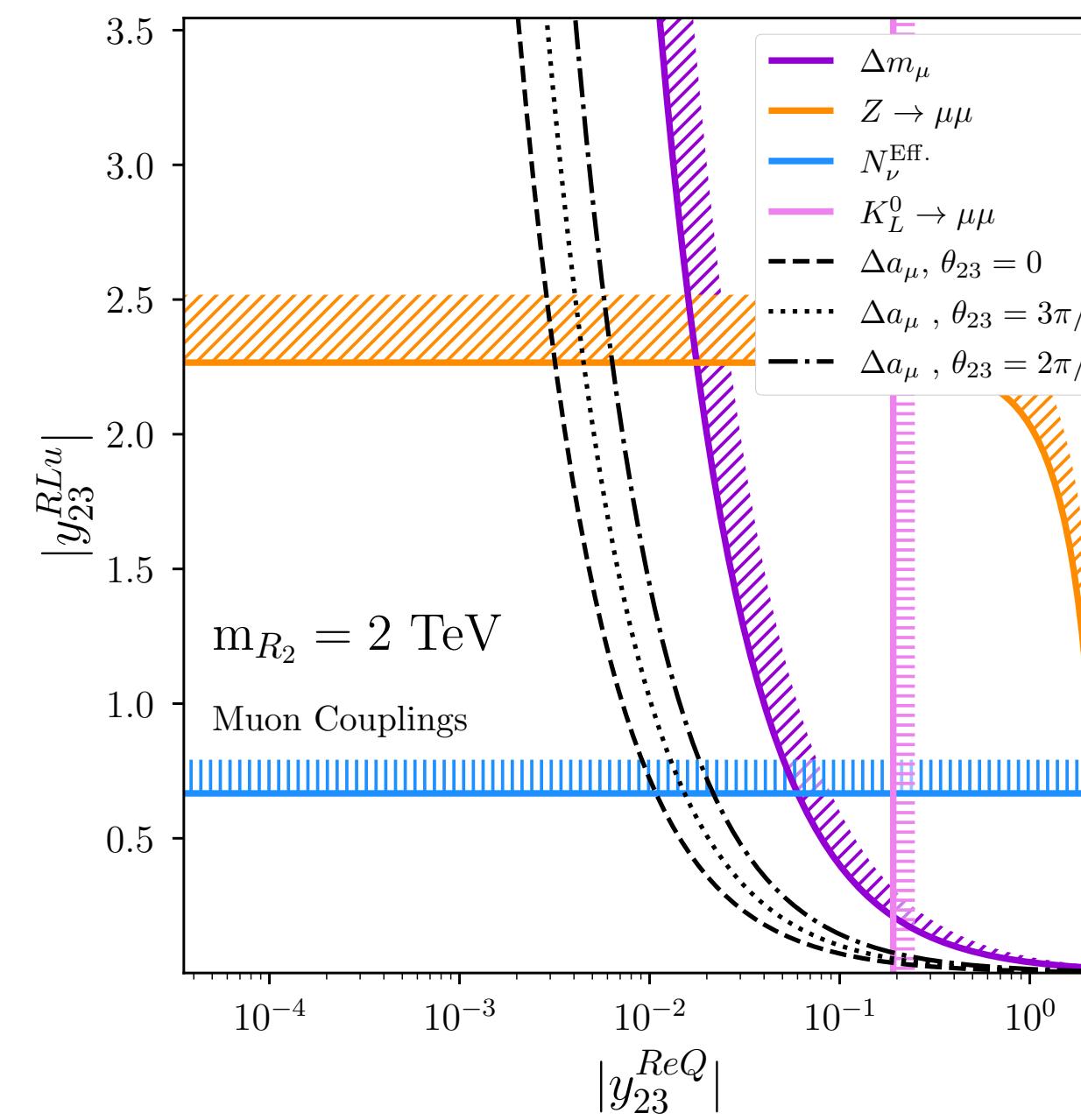
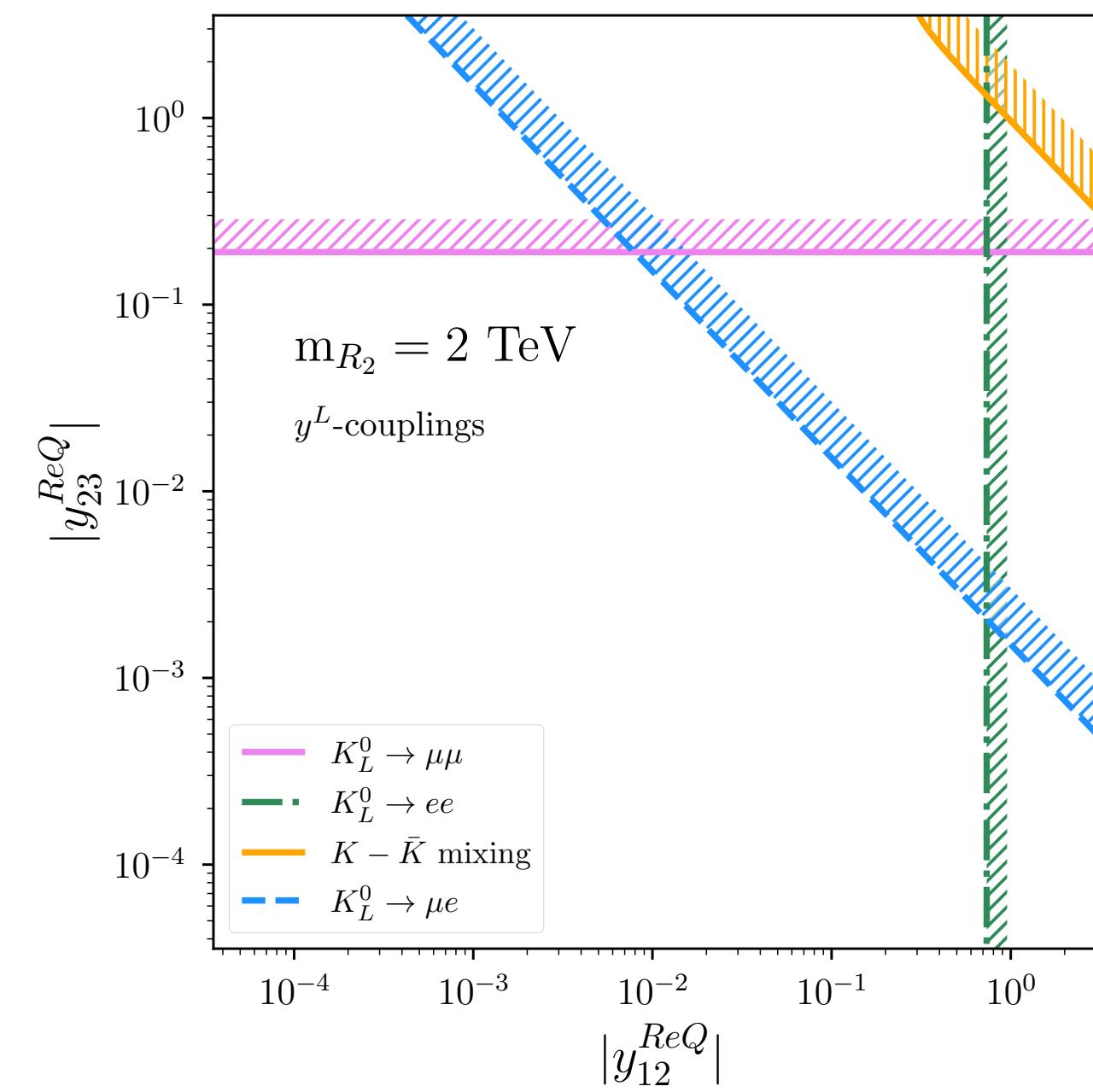
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Other constraints for R2

$$\mathcal{L}_{\text{int}}^{R_2} = (\overline{L_L} \lambda_{Lu} u_R + \overline{e_R} \lambda_{eQ} Q_L) R_2^\dagger + h.c.$$



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

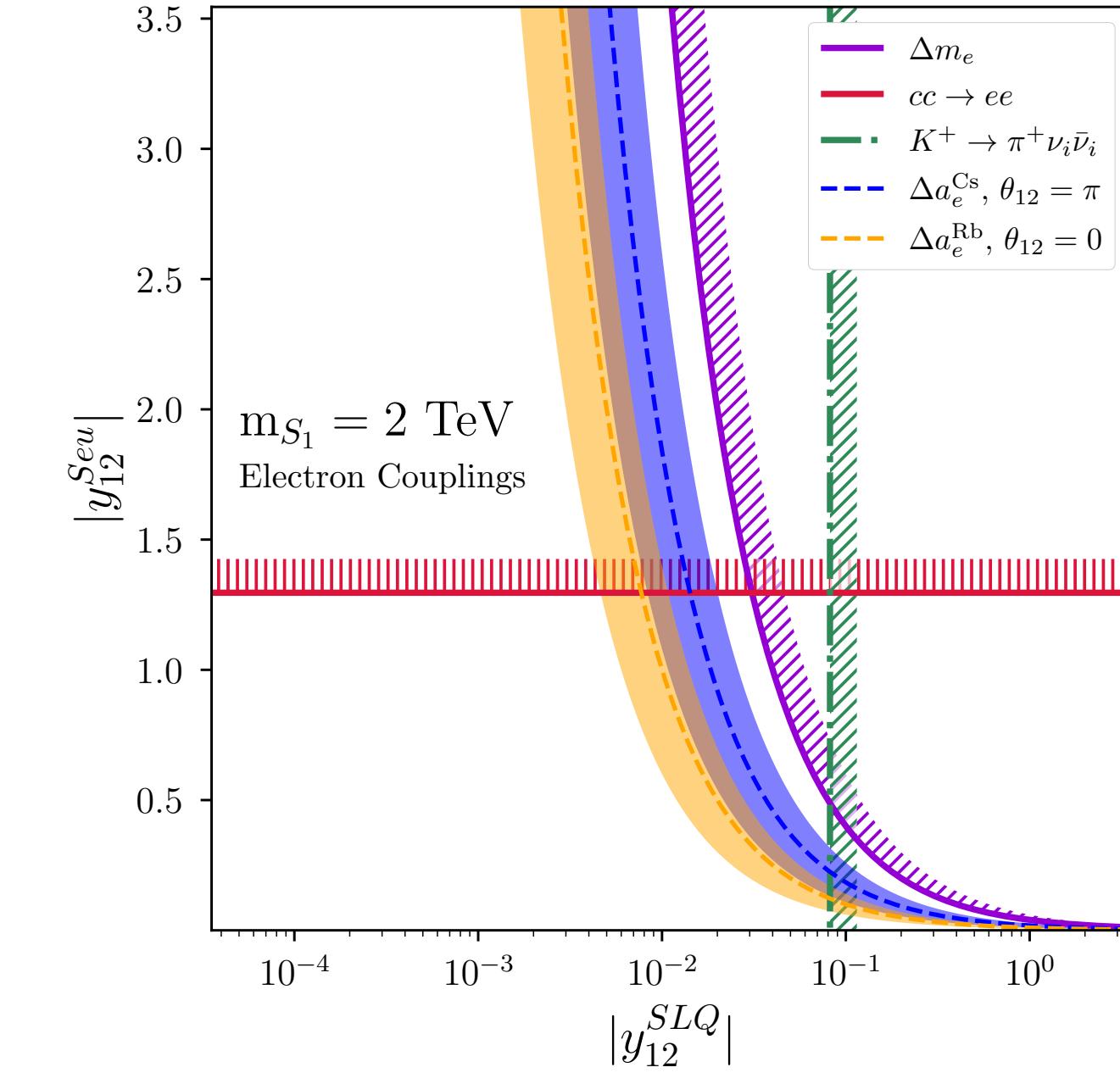
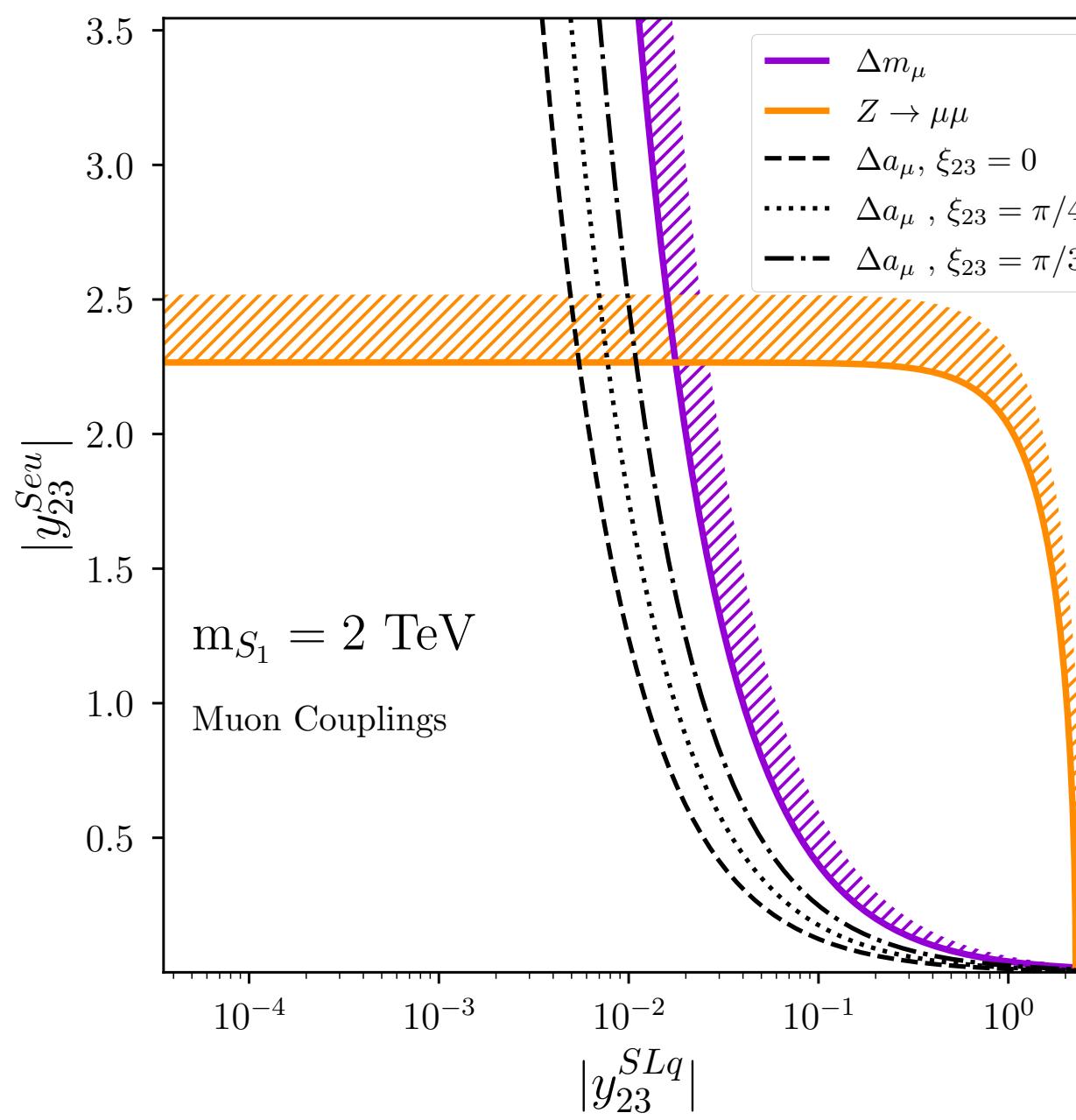
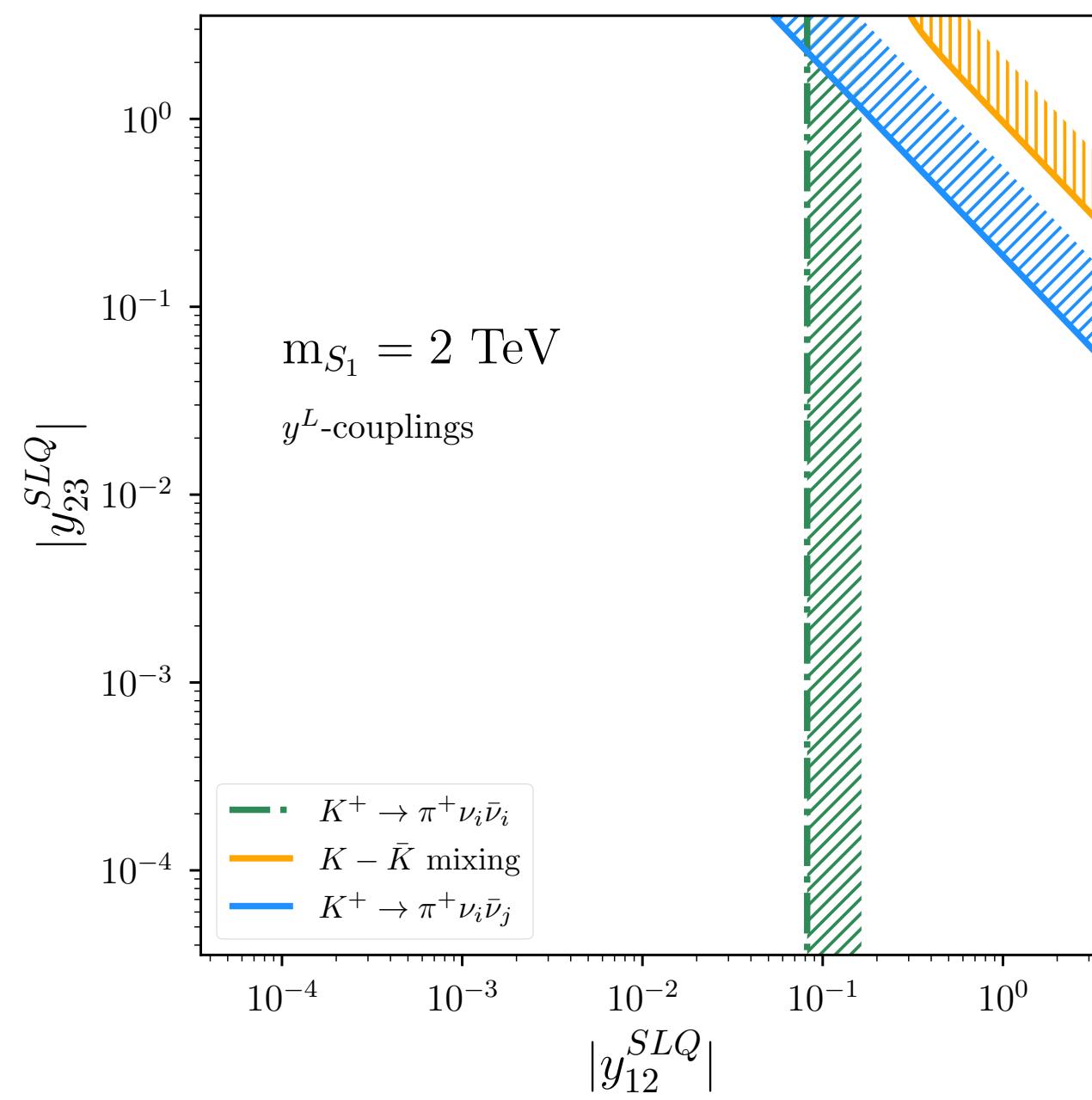


Other constraints for S1

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



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

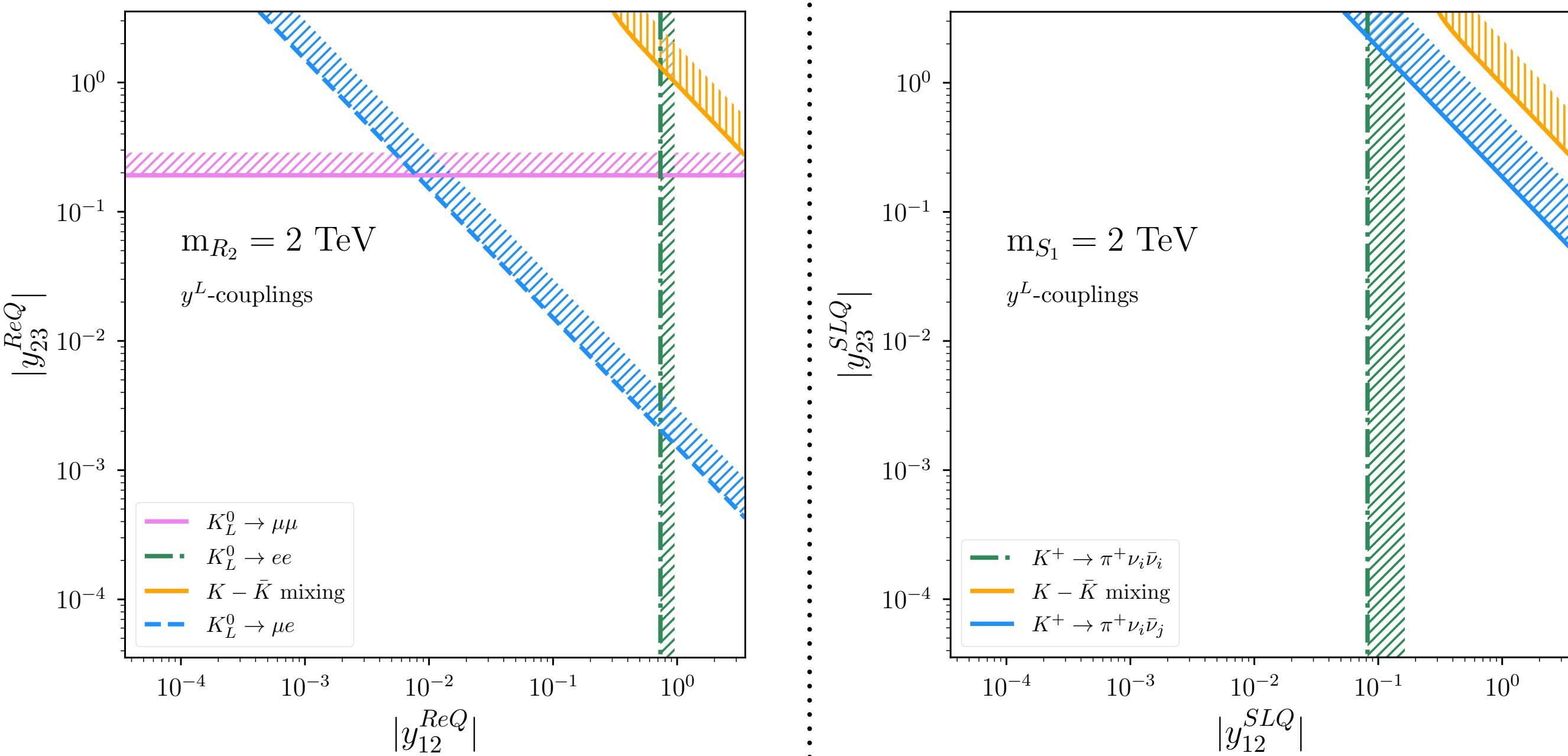


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$K_L^0 \rightarrow e^+ e^-$	Br	$(9_{-4}^{+6}) \times 10^{-12}$
$K_L^0 \rightarrow \mu^+ \mu^-$	Br	$(6.84 \pm 0.11) \times 10^{-9}$
$K_L^0 \rightarrow \mu^+ e^-$	Br	$< 4.7 \times 10^{-12}$
$K_0\bar{K}_0$ mixing	$ \epsilon_K $	$(2.228 \pm 0.011) \times 10^{-3}$
	ΔM_K	$(3.484 \pm 0.006) \times 10^{-12}$
$pp \rightarrow \ell\ell$	$ y_{12}^{Seu} $	$< 0.648 \hat{m}_\phi$
[68]	$ y_{12}^{RLu} $	$< 0.524 \hat{m}_\phi$

TABLE III. Processes most constraining on this model. Values quoted without citation are from PDG [69]. Constraints from $pp \rightarrow \ell\ell$ are derived from Table 1 of reference [68].

Phenomenological study

- An example of this, is via the study of the left-handed couplings:



$$\mathcal{L}_{\text{int}}^{R_2} = (\overline{L}_L \lambda_{Lu} u_R + \overline{e}_R \lambda_{eQ} Q_L) R_2^\dagger + h.c.$$

$$\mathcal{L}_{\text{int}}^{S_1} = (\overline{L}_L^c \lambda_{LQ} Q_L + \overline{e}_R^c \lambda_{eu} u_R) S_1^\dagger + h.c.,$$

See [2002.12544](#) and [2110.03707](#) for further detail