Vector-like extension of the Standard Model with extra scalars

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in collaboration with
A. E. Cárcamo Hernández, Huchan Lee, Daniele Rizzo

arXiv: 2309.13968

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National Science Centre Poland

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The model of flavour

S.F.King, JHEP 09 (2018) 069

Field	Q_{iL}	u_{iR}	d_{iR}	L_{iL}	e_{iR}	Q_{4L}	u_{4R}	d_{4R}	L_{4L}	e_{4R}	ν_{4R}	$\widetilde{Q}_{4R}$	$\widetilde{u}_{4L}$	$\widetilde{d}_{4L}$	$\widetilde{L}_{4R}$	$\widetilde{e}_{4L}$	$\widetilde{\nu}_{4L}$	ϕ	H_u	H_d
$SU(3)_C$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$
$U(1)_Y$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	0	$-\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$	-1	0	0	$\frac{1}{2}$	$-\frac{1}{2}$
$U(1)_X$	0	0	0	0	0	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	1	-1	-1

Standard Model

New Physics: VL fermions + 2 scalars

COMPLEX … BUT STILL MINIMAL

- **SM Yukawa couplings forbidden** by global U(1)
- Masses generated via **mixing** with vector-like NP fermions
- A lot of NP parameters (Yukawa couplings and VL masses)…
- … but constrained by the SM

$$\mathcal{M}_e = \left(\begin{array}{c|ccccc} & e_{1R} & e_{2R} & e_{3R} & e_{4R} & \widetilde{e}_{4R} \\ \hline e_{1L} & 0 & 0 & 0 & 0 & 0 \\ e_{2L} & 0 & 0 & 0 & y^e_{24}\frac{v_d}{\sqrt{2}} & 0 \\ e_{3L} & 0 & 0 & 0 & y^e_{34}\frac{v_d}{\sqrt{2}} & -x^L_{34}\frac{v_\phi}{\sqrt{2}} \\ e_{4L} & 0 & 0 & y^e_{43}\frac{v_d}{\sqrt{2}} & 0 & -M^L_4 \\ \widetilde{e}_{4L} & 0 & x^e_{42}\frac{v_\phi}{\sqrt{2}} & x^e_{43}\frac{v_\phi}{\sqrt{2}} & M^e_4 & 0 \end{array}\right)$$

$\langle H^0_u \rangle = v_u/\sqrt{2}, \quad \langle H^0_d \rangle = v_d/\sqrt{2}, \quad \langle \phi \rangle = v_\phi/\sqrt{2}$

Fermion masses

S.F.King, JHEP 09 (2018) 069
A.Cárcamo Hernández, KK, H.Lee, D.Rizzo, arXiv:2309.13968

3rd and 2nd generations of the SM:

$$m_t \approx \frac{1}{\sqrt{2}} \frac{y^u_{43} x^Q_{34} v_\phi v_u}{\sqrt{(x^Q_{34} v_\phi)^2 + 2(M^Q_4)^2}}, \qquad m_c \approx \frac{y^u_{24} x^u_{42} v_\phi v_u}{2 M^u_4}$$

$$m_b \approx \frac{1}{\sqrt{2}} \frac{y^d_{43} x^Q_{34} v_\phi v_d}{\sqrt{(x^Q_{34} v_\phi)^2 + 2(M^Q_4)^2}}, \qquad m_s \approx \frac{y^d_{24} x^d_{42} v_\phi v_d}{2 M^d_4}$$

$$m_\tau \approx \frac{1}{\sqrt{2}} \frac{y^e_{43} x^L_{34} v_\phi v_d}{\sqrt{(x^L_{34} v_\phi)^2 + 2(M^L_4)^2}}, \qquad m_\mu \approx \frac{y^e_{24} x^e_{42} v_\phi v_d}{2 M^e_4} .$$

large to fit the top mass

small to fit the charm mass

$v_u/v_d >> 1$ to get $m_t >> m_b$

1st generation is massless with 1 VL family
can be easily extended by another VL: A.C.Hernández, S.F.King, and H.Lee, Phys. Rev. D 103, 115024 (2021)

Vector-like NP fermions:

Colored VL fermions heavier than 1400 GeV (LHC bounds) $\rightarrow M_4^Q,\ M_4^U,\ M_4^D > 1200\,\mathrm{GeV}$

$$M_{E_1} \approx \sqrt{(M_4^L)^2 + \frac{1}{2}(v_\phi x^L_{34})^2}, \qquad M_{E_2} = \sqrt{(M_4^e)^2 + \frac{1}{2}(v_\phi x^e_{43})^2 + \frac{1}{2}(v_\phi x^e_{42})^2}$$

$$M_{N_1} = M_{N_2} \approx M_4^\nu, \qquad M_{N_3} = M_{N_4} \approx \sqrt{(M_4^L)^2 + \frac{1}{2}(v_\phi x^L_{34})^2}$$

- Neutrinos 1,2 can be the lightest (DM?)
- Neutrinos 3,4 mass degenerate with charged VL leptons

CKM mixing matrix

5x5 mixing matrix → 3x3 CKM matrix

A.Cárcamo Hernández, KK, H.Lee, D.Rizzo
arXiv:2309.13968

$$V_{\rm CKM}^{3\times 3} \approx \begin{pmatrix} 1 - x_{ud}^2/2 & x_{ud} & x_{ud}x_d \\ -x_{ud} & 1 - x_{ud}^2/2 & x_d - x_u \\ -x_u x_{ud} & x_u - x_d & 1 \end{pmatrix} \qquad x_d = \frac{y_{24}^d x_{43}^d M_4^Q}{y_{43}^d x_{34}^Q M_4^d} \qquad x_u = \frac{y_{24}^u x_{43}^u M_4^Q}{y_{43}^u x_{34}^Q M_4^u} \qquad x_{ud} = \frac{y_{14}^d}{y_{24}^d}$$

order one

Comparing with the experiment:

- to fit the Cabibbo angle $y_{14}^d \approx 0.22\, y_{24}^d$
- to fit V_{13} one needs $x_d \approx 0.017 \quad x_u \approx -0.023$

$$\frac{|V_{\rm CKM}^{\rm exp}| - |V_{\rm CKM}^{3\times 3}|}{\delta |V_{\rm CKM}^{\rm exp}|} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.04 & 0 \\ 8.88 & 0.23 & 0.01 \end{pmatrix}$$

← difficult to fit with 1 VL family

1 extra VL family needed

Phenomenology

Studied in the context of ...

Flavor anomalies in $b \to s$ transitions — S.F.King, JHEP 09, 069 (2018); H.Lee, A.Cárcamo Hernández, arXiv: 2207.01710

Muon g-2 anomaly — H.Lee, A.Cárcamo Hernández (2022), 2207.01710.; A.Cárcamo Hernández, S.F.King, H.Lee, S.J.Rowley, Phys. Rev. D 101, 115016 (2020); A.Cárcamo Hernández, S.F.King, H.Lee, Phys. Rev. D 103, 115024 (2021)

Flavour Changing Neutral Currents — A.C.Hernández, S.F.King, H.Lee, Phys. Rev. D 105, 015021 (2022)

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… but many things were wrong

- Scalar potential ``boundedness from below''
- Alignment limit (the lightest scalar is the SM Higgs)
- Perturbativity of the Yukawa and scalar couplings
- Caluclation of the NP contrbution to muon g-2

→ **needs to be redone**

A.Cárcamo Hernández, KK, H.Lee, D.Rizzo
arXiv:2309.13968

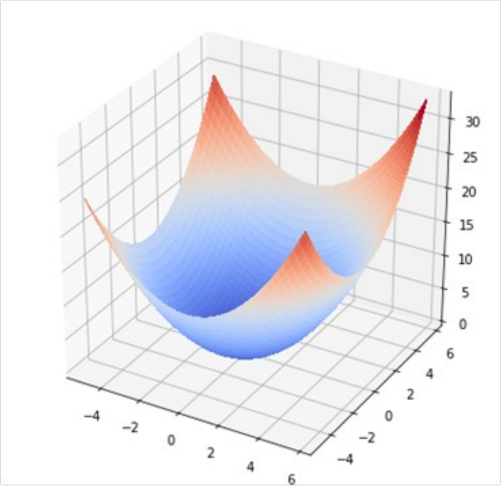
Scalar sector constraints

$$V = \mu_u^2 (H_u^\dagger H_u) + \mu_d^2 (H_d^\dagger H_d) + \mu_\phi^2 (\phi^* \phi) - \frac{1}{2}\mu_{\rm sb}^2 \left(\phi^2 + \phi^{*2}\right)$$
$$+ \frac{1}{2}\lambda_1 (H_u^\dagger H_u)^2 + \frac{1}{2}\lambda_2 (H_d^\dagger H_d)^2 + \lambda_3 (H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4 (H_u^\dagger H_d)(H_d^\dagger H_u)$$
$$- \frac{1}{2}\lambda_5 (\epsilon_{ij} H_u^i H_d^j \phi^2 + \text{H.c.}) + \frac{1}{2}\lambda_6 (\phi^*\phi)^2 + \lambda_7 (\phi^*\phi)(H_u^\dagger H_u) + \lambda_8 (\phi^*\phi)(H_d^\dagger H_d)$$

quartic couplings determine the shape of scalar potential

$$\lambda_8 + \sqrt{\lambda_2 \lambda_6} > 0$$
$$\lambda_7 + \sqrt{\lambda_1 \lambda_6} > 0$$
$$\lambda_3 + \sqrt{\lambda_2 \lambda_1} > 0$$
$$\lambda_3 + \lambda_4 + \sqrt{\lambda_2 \lambda_1} > 0$$
$$-\frac{1}{4}\frac{(\mathrm{Re}\,\lambda_5)^2 + (\mathrm{Im}\,\lambda_5)^2}{\lambda_a} + \lambda_4 > 0$$
$$4\lambda_b^2 - (\mathrm{Re}\,\lambda_5)^2 + \mathrm{Re}\,\lambda_5\,\mathrm{Im}\,\lambda_5 > 0$$
$$4\lambda_b^2 - (\mathrm{Im}\,\lambda_5)^2 + \mathrm{Re}\,\lambda_5\,\mathrm{Im}\,\lambda_5 > 0$$

V must be bounded from below



3 neutral scalar fields from diagonalization of:

$$\mathbf{M}^2_{\rm CP-even} = \begin{pmatrix} \lambda_1 v_u^2 - \lambda_5 \frac{v_d v_\phi^2}{4 v_u} & \lambda_3 v_u v_d + \lambda_5 \frac{v_\phi^2}{4} & \lambda_7 v_u v_\phi + \lambda_5 \frac{v_d v_\phi}{2} \\ \lambda_3 v_u v_d + \lambda_5 \frac{v_\phi^2}{4} & \lambda_2 v_d^2 - \lambda_5 \frac{v_u v_\phi^2}{4 v_d} & \lambda_8 v_d v_\phi + \lambda_5 \frac{v_u v_\phi}{2} \\ \lambda_7 v_u v_\phi + \lambda_5 \frac{v_d v_\phi}{2} & \lambda_8 v_d v_\phi + \lambda_5 \frac{v_u v_\phi}{2} & \lambda_6 v_\phi^2 \end{pmatrix}$$

→ ***h_1, h_2, h_3***

alignment limit:

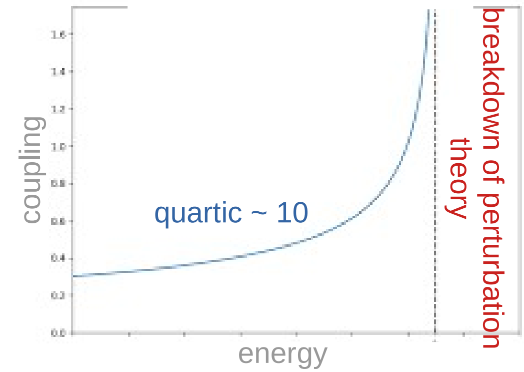
$$\lambda_8 \cos^2\beta + \lambda_7 \sin^2\beta + \lambda_5 \sin\beta\cos\beta = 0$$
$$\lambda_2 \cos^2\beta - \lambda_1 \sin^2\beta - \lambda_3(\cos^2\beta - \sin^2\beta) = 0\,,$$

RGE perturbativity bounds

Naive perturbativity:

gauge,Yukawa coupling (NP) < $\sqrt{4\pi}$
quartic coupling (NP) < 4π

for the lagrangian parameters



the problem:

NP must be an effective theory → UV completion required at the energy scale close to NP would affect pheno predictions

RGE perturbativity:

UV completion does not affect NP-scale pheno (muon g-2) ⇨ the scale of UV completion must be above ~ 50 TeV

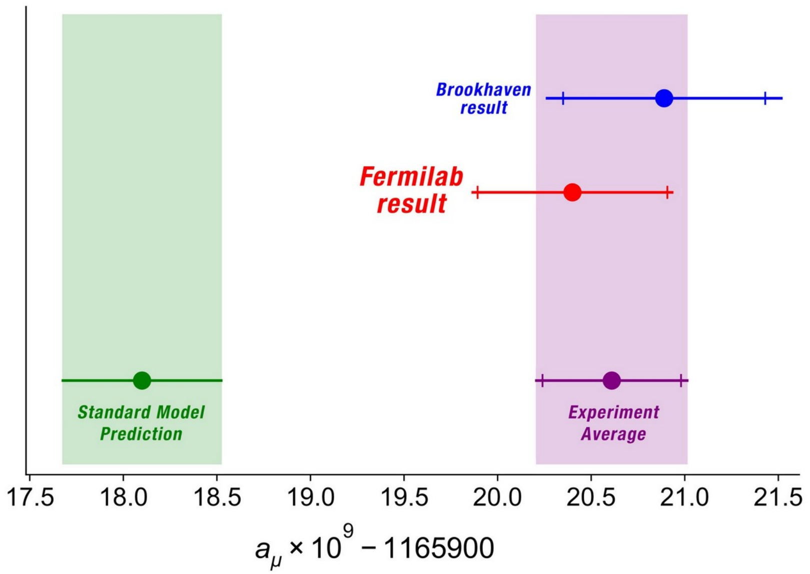
gauge,Yukawa coupling (Λ) < $\sqrt{4\pi}$
quartic coupling (Λ) < 4π
⇨
gauge,Yukawa coupling (NP) < 1
quartic coupling (NP) < 2

Muon g-2 anomaly

Measured value at BNL (2006):

Bennet *et al*, Phys. Rev. D 73 (2006) 072003 (hep-ex/0602035)

$$a_\mu^{\rm BNL} = (116592089 \pm 63) \times 10^{-11}$$



Measured value at FNAL (2021):

Muon g-2 Collaboration, Phys. Rev. Lett. 126 (2021) 141801
Muon g-2 Collaboration, arXiv: 2308.06230

$$a_\mu^{\rm FNAL} = (116592055 \pm 24) \times 10^{-11}$$

$$\Delta\, a_\mu = (24.9 \pm 4.8) \times 10^{-10}$$

New Physics?

discrepancy at ~ 5.1 σ!

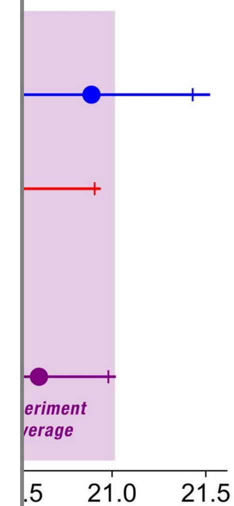
Muon g-2 anomaly

Measu
Bennet e

a_μ^{BI}

Measu
Muon g-2

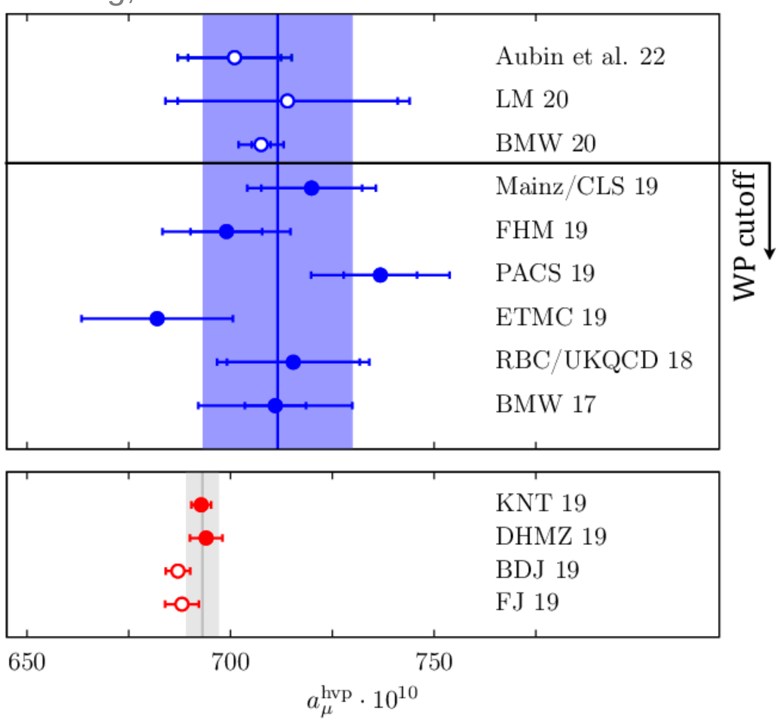
a_μ^{FI}



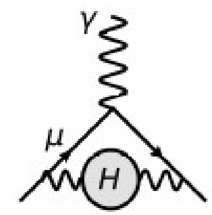
sics?

BUT BE(A)WARE OF THE LATTICE

H.Wittig, arXiv:2306.04165



hadronic vacuum polarisation contribution **underestimated**?



muon (g-2) anomaly **reduced to 1.5-2 σ**

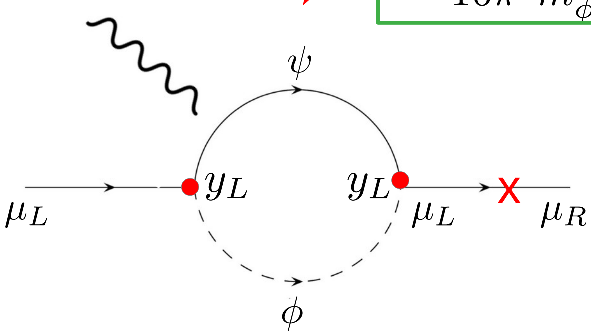
tension with the data-driven dispersive methods of 2-4 σ
New Anomaly?

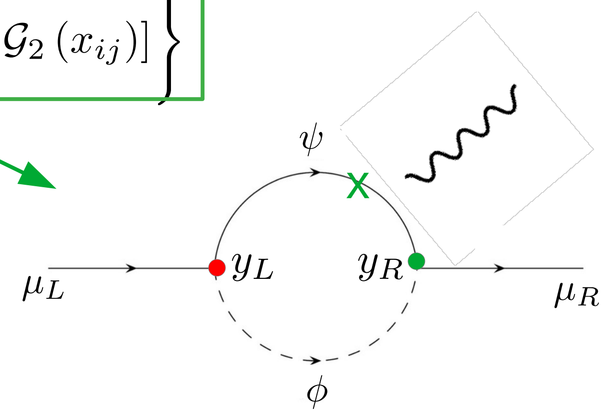
g-2 with scalars and fermions

1-loop contribution from scalar(s) ϕ_i and VL fermions ψ_j

$$\delta(g-2)_\mu = \sum_{i,j} \left\{ -\frac{m_\mu^2}{16\pi^2 m_{\phi_i}^2} \left(|y_L^{ij\mu}|^2 + |y_R^{ij\mu}|^2\right) \left[Q_j \mathcal{F}_1(x_{ij}) - Q_i \mathcal{G}_1(x_{ij})\right] - \frac{m_\mu\, m_{\psi_j}}{16\pi^2 m_{\phi_i}^2} \mathrm{Re}\left(y_L^{ij\mu} y_R^{ij\mu *}\right) \left[Q_j \mathcal{F}_2(x_{ij}) - Q_i \mathcal{G}_2(x_{ij})\right] \right\}$$

$x_{ij} = m_{\psi_j}^2 / m_{\phi_i}^2$





- minimal: 1 VL lepton and 1 scalar
- $m_\psi,\, m_\phi \sim \mathcal{O}(100\,\mathrm{GeV})$
- Yukawa couplings > 1
- **excluded by the LHC** see P. Athron et al., 2104.03691 for the most recent results
- **Landau Pole** e.g. KK. E.Sessolo, 1707.00753

- at least two reps. of VL needed
- parametrically enhanced
- LHC bounds easily avoided...

We have VL lepton SU(2) doublet and singlet

Scanning methodology

Input parameters:

				Scalar sector					
$\tan\beta$	$[2, 50]$	v_ϕ	$[1000, 1500]$	μ^2_{sb}	$[4, 64] \times 10^4$	λ_2	$[-2.0, +2.0]$	λ_3	$[0.24, 0.28]$
λ_4	$[-2.0, +2.0]$	λ_5	$[-0.2, 0.0]$	λ_6	$[-2.0, +2.0]$	λ_7	$[-0.01, +0.01]$	λ_8	$[-1.0, +1.0]$
				Lepton sector					
y^e_{24}	$[-0.7, +0.7]$	y^e_{43}	$[-1.0, +1.0]$	y^ν_{14}	$[-1.0, +1.0] \times 10^{-10}$	y'^ν_{14}	$[-1.0, +1.0]$	M^e_4	$\pm [200, 1000]$
y^e_{34}	$[-1.0, +1.0]$	x^e_{42}	$[-1.0, +1.0]$	y^ν_{24}	$[-1.0, +1.0] \times 10^{-10}$	y'^ν_{24}	$[-1.0, +1.0]$	M^ν_4	$\pm [200, 1000]$
x^L_{34}	$[-1.0, +1.0]$	x^e_{43}	$[-1.0, +1.0]$	y^ν_{34}	$[-1.0, +1.0] \times 10^{-10}$	y'^ν_{34}	$[-1.0, +1.0]$	M^L_4	$\pm [200, 1000]$
				Quark sector					
y^u_{24}	$[-1.0, +1.0]$	y^u_{43}	$[-1.4, +1.4]$	y^d_{14}	$[-0.7, +0.7]$	y^d_{43}	$[-1.0, +1.0]$	M^d_4	$\pm [1200, 4000]$
y^u_{34}	$[-1.4, +1.4]$	x^u_{42}	$[-1.0, +1.0]$	y^d_{24}	$[-1.0, +1.0]$	x^d_{42}	$[-1.0, +1.0]$	M^u_4	$\pm [1200, 4000]$
x^Q_{34}	$[-1.0, +1.0]$	x^u_{43}	$[-1.4, +1.4]$	y^d_{34}	$[-1.0, +1.0]$	x^d_{43}	$[-1.0, +1.0]$	M^Q_4	$\pm [1200, 4000]$

We minimize the χ^2 function:

$$\chi^2 = \sum_i \frac{\left(\mathcal{O}_i^{\text{model}} - \mathcal{O}_i^{\text{cen}}\right)^2}{\left(\mathcal{O}_i^{\text{err}}\right)^2}$$

- SM fermions masses
- CKM matrix angles
- Muon g-2

⇒ **benchmark points**

Typical NP spectra

Fermion sector:

VL quarks

U_1: ~1500 GeV
D_1: ~1500 GeV
set by M^Q
U_2: ~1700-1900 GeV
D_2: ~2900-3600 GeV to suppress x_d (CKM)

masses determined by fitting the SM

VL leptons

$N_{1,2}$: ~200 GeV
$N_{3,4}$: ~500-600 GeV
E_1: ~500-600 GeV
set by M^L
E_2: ~550-650 GeV

(neutrino) masses determined by muon g-2

Scalar sector:

neutral scalars

h_1: 125 GeV
h_2: ~400 GeV
h_3: ~600-800 GeV

pseudo-scalars

a_1: ~*400* GeV
a_2: ~450-600 GeV

charged scalars

$h_\pm$: ~*400* GeV

scalar masses determined by muon *g-2*

Typical NP spectra

Fermion sector:

LHC?

VL quarks

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charged scalars

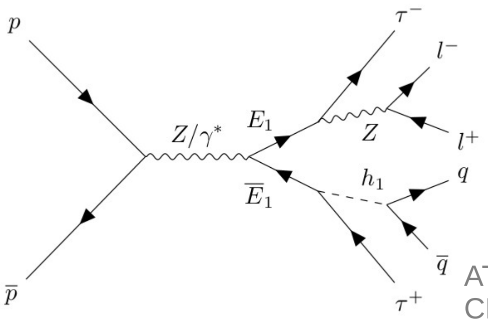
$h_{\pm}$: ~400 GeV

scalar masses determined by muon *g-2*

LHC bounds

VL leptons:

decay predominantly to muons … but no dedicated experimental analysis



BR to taus low (<10%) … cross section 3-4 orders of magnitude below the current bounds

ATLAS: JHEP 07, 118 (2023)
CMS: Phys. Rev. D 100, 052003 (2019)

NP scalars:

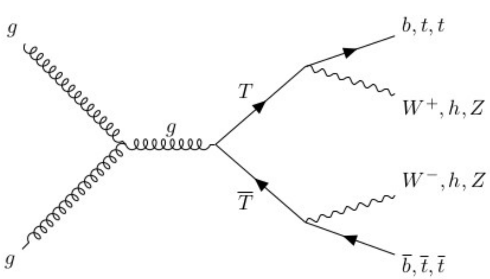
$h_2 \to \tau^+\tau^-$
$a_1 \to \tau^+\tau^-$
} most promissing channel

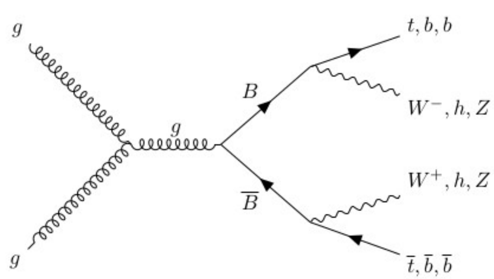
$$\frac{\text{predicted CS}}{\text{experimental}_{95\%}\text{ CS}} = 0.6$$

can be tested in Run 3

VL quarks:

ATLAS: Eur. Phys. J. C 83, 719 (2023)
CMS: JHEP 07, 020 (2023)





cross section one order of magnitude smaller than the current bounds
can be tested in Run 3

NP contributions to muon g-2

Contributions to $\Delta a_\mu \times 10^9$							
Charged scalars				CP-even scalars			
Loop	BP1	BP2	BP3	Loop	BP1	BP2	BP3
$h^\pm, N_{1,2}$	-1.076	-0.792	-0.942	h_1, E_1	-0.003	-0.001	-0.009
$h^\pm, N_{3,4}$	3.300	2.898	3.153	h_1, E_2	0.003	0.001	0.009
$h^\pm, N_{\text{tot}}$	2.225	2.106	2.211	h_2, E_1	-0.409	-0.520	-0.969
CP-odd scalars				h_2, E_2	0.437	0.548	0.994
a_1, E_1	0.425	0.528	0.938	h_3, E_1	0.018	0.115	0.076
a_1, E_2	-0.544	-0.611	-1.529	h_3, E_2	-0.017	-0.127	-0.076
a_2, E_1	-0.033	-0.135	-0.071	h, E_{tot}	0.032	0.027	0.025
a_2, E_2	0.110	0.196	0.621	Total			
a, E_{tot}	-0.015	-0.023	-0.041	Δa_μ	2.215	2.101	2.196

Dominant contribution from the charged scalar-neutrino loops

NP neutrino Yukawa couplings not constrained by the SM – can become large

Not caluclated in the prevous studies of the model ...

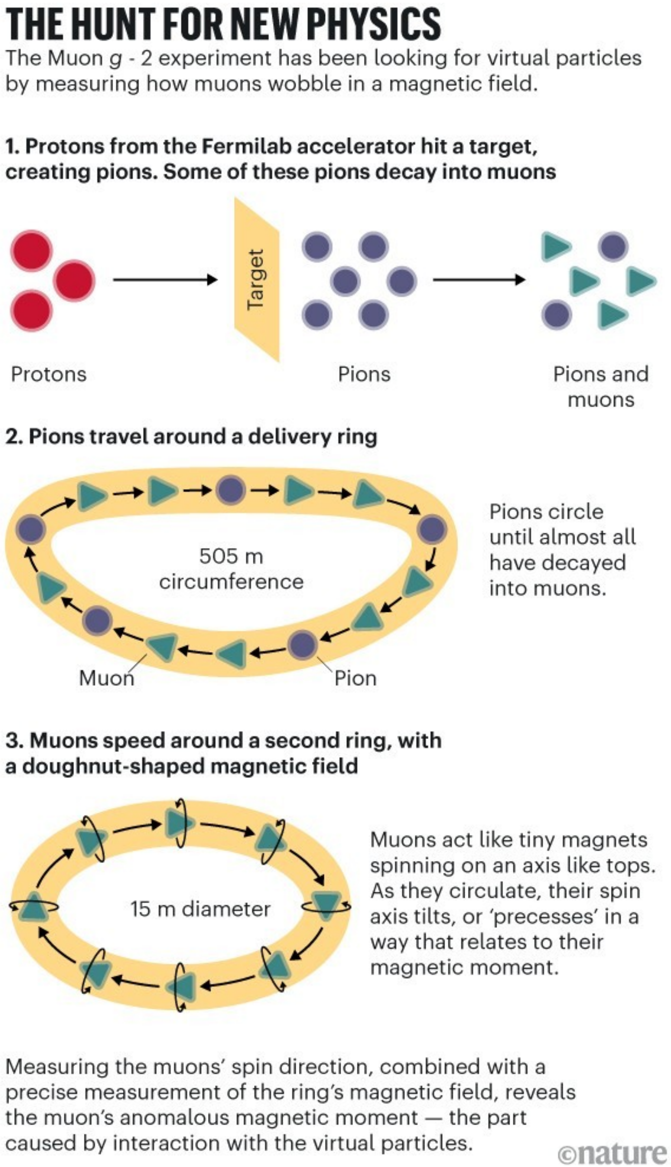
Cancellations between the (pseudo) scalar-charged lepton loops

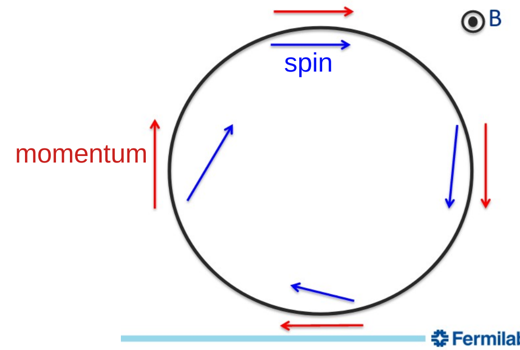
ex: L. Darmé, K. Kowalska, L. Roszkowski, and E. M. Sessolo, JHEP 10, 052 (2018)
K. Kowalska and E. M. Sessolo, Phys. Rev. D 103, 115032 (2021)

To take home

- NP model to explain the **SM fermion masses and mixings**
- Strong **constraints** on the Yukawa couplings **from perturbativity**
- **Heavy neutrino-charged scalar** contribution to muon g-2 is dominant
- Possible discovery/exclusion in the **VL quark** and **scalar tau-channel** Run 3 LHC searches

Muon g-2 measurement





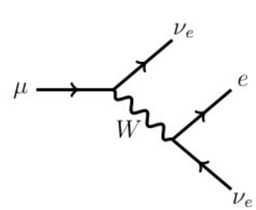
Brendan Kiburg,
talk at the University of Warsaw Colloquium

muon spin precession frequency
relative precession frequency of the spin with respect to the momentum

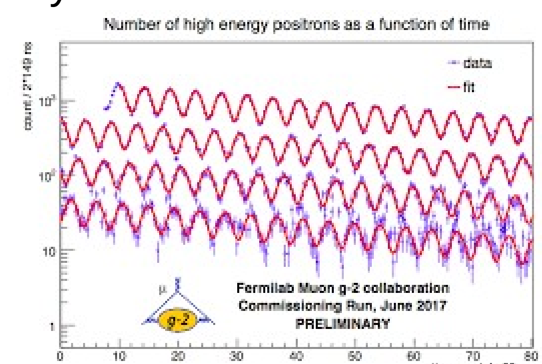
$$\omega_a = \frac{e\,B}{m_\mu} a_\mu$$

step 1: measure magnetic field

step 2: measure precession frequency

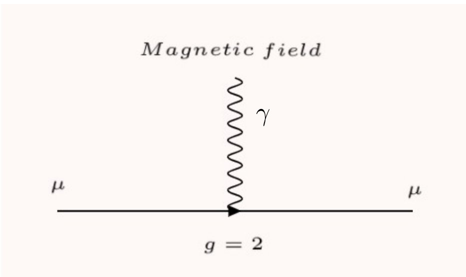


parity not conserved → positrons emitted in the direction correlated to the spin



fit to get ωa $F(t) = N_0 e^{-t/\gamma\tau_\mu}\left[1 + A_0 \cos(\omega_a^m t + \phi_0)\right]$

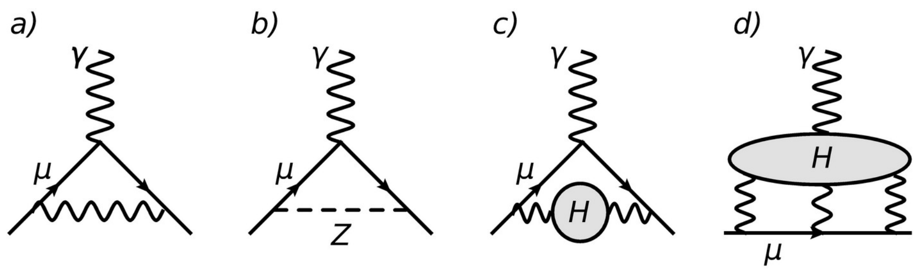
Muon g-2 - theory



$$\vec{\mu} = g\,\frac{q}{2m}\,\vec{S}$$

in quantum mechanics: $g = 2$

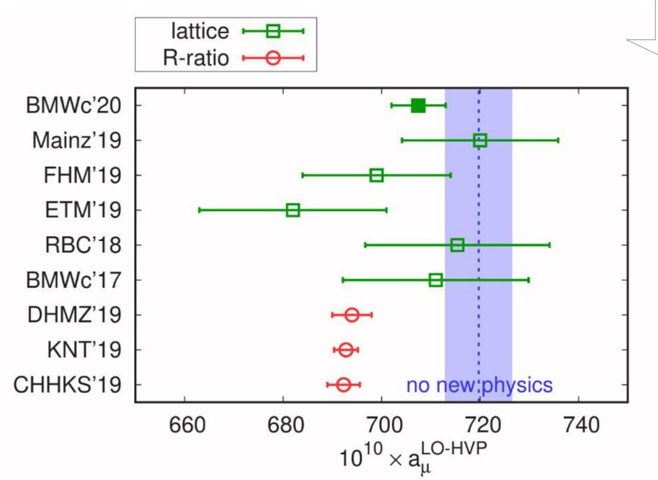
in QFT loop effects can shift g



QED EW HAD VP HAD LBL

anomalous magnetic moment: $a = \dfrac{g-2}{2}$

subject to uncertainties



Standard Model value:

Aoyama, Kinoshota, Nio, Atoms 7 (2019) 28

$$a_\mu^{\rm SM} = (116591810 \pm 43) \times 10^{-11}$$