Global analysis and LHC study of a vector-like extension of the Standard Model with extra scalars

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Based on

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in collaboration with

Antonio E. Cárcamo Hernández, Kamila Kowalska, Huchan Lee

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However, many things were not entirely correct ...

Vacuum Stability

Perturbativity

Alignment limit

Muon g-2

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In this work, we **re-assess** the previous analysis and add some **new results**.

The model

Particle Content

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
$\mathrm{SU}(3)_C$	$\mathbf{3}$	$\overline{\mathbf{3}}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\overline{\mathbf{3}}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{SU}(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$
$\mathrm{U}(1)_Y$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	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	$\frac{1}{2}$	$-\frac{1}{2}$
$\mathrm{U}(1)_X$	0	0	0	0	0	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	1	-1	-1

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$\mathrm{SU}(3)_C$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\bar{\mathbf{3}}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\bar{\mathbf{3}}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{SU}(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$
$\mathrm{U}(1)_Y$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	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	$\frac{1}{2}$	$-\frac{1}{2}$
$\mathrm{U}(1)_X$	0	0	0	0	0	1	1	1	1	1	1	-1	-1	-1	-1	-1	-1	1	-1	-1

Mass Matrix for the fermions

This element is 0 in the up and charged lepton mass matrices

$$
\mathrm{M}_D = \left(\begin{array}{c|ccccc}
 & d_{1R} & d_{2R} & d_{3R} & d_{4R} & \widetilde{Q}_{4R} \\
\hline
Q_{1L} & 0 & 0 & 0 & y^d_{14}\langle H^0_d\rangle & 0 \\
Q_{2L} & 0 & 0 & 0 & y^d_{24}\langle H^0_d\rangle & 0 \\
Q_{3L} & 0 & 0 & 0 & y^d_{34}\langle H^0_d\rangle & x^d_{34}\langle\phi\rangle \\
Q_{4L} & 0 & 0 & y^d_{43}\langle H^0_d\rangle & 0 & M^Q_4 \\
\widetilde{d}_{4L} & 0 & x^d_{42}\langle\phi\rangle & x^d_{43}\langle\phi\rangle & M^d_4 & 0
\end{array}\right)
$$

CKM matrix analytically computed for the first time in our work

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

Mass generation for fermions

Mass of 3rd generation fermions

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

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Mass insertion approximation

$$34 \approx \frac{m_t}{m_b} \approx \frac{y^u_{43}}{y^d_{43}} \tan\beta$$

$$\tan\beta \approx \mathcal{O}(1) \quad \& \quad y^u_{43} >> y^d_{43}$$

Large hierarchy

$$\tan\beta \approx \mathcal{O}(10) \quad \& \quad y^u_{43}\,,\, y^d_{43} \approx \mathcal{O}(1)$$

The Scalar Potential

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

Spectrum:

3 massive CP-Even

2 massive CP-Odd + 1 Goldstone

1 massive charged + 1 Goldstone

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\begin{aligned}
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_{sb}^2\left(\phi^2 + \phi^{*2}\right) \\
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Alignment limit:

$$\lambda_2 = \lambda_3 + \tan^2\beta(\lambda_1 - \lambda_3) \qquad \lambda_8 = -\tan\beta\left(\lambda_7 \tan\beta + \lambda_5\right)$$

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$$\lambda_3 \approx \lambda_1 + \mathcal{O}(1/\tan^2\beta) \qquad \lambda_7 \sim \mathcal{O}(1/\tan^2\beta) \qquad \lambda_5 \sim \mathcal{O}(1/\tan\beta)$$

Vacuum Stability

$$V = \mu_u^2(H_u^\dagger H_u) + \mu_d^2(H_d^\dagger H_d) + \mu_\phi^2(\phi^*\phi) - \frac{1}{2}\mu_{sb}^2\left(\phi^2 + \phi^{*2}\right)$$
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“Boundedness from below”

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$$\lambda_3 + \sqrt{\lambda_2\lambda_1} > 0$$
$$\lambda_3 + \lambda_4 + \sqrt{\lambda_2\lambda_1} > 0$$

These were already implemented in previous works

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$$\lambda_8 + \sqrt{\lambda_2\lambda_6} > 0$$
$$\lambda_7 + \sqrt{\lambda_1\lambda_6} > 0$$

$$-\frac{1}{4}\frac{(\mathrm{Re}\lambda_5)^2 + (\mathrm{Im}\lambda_5)^2}{\lambda_a} + \lambda_4 > 0$$
$$4\lambda_b^2 - (\mathrm{Re}\lambda_5)^2 + \mathrm{Re}\lambda_5\mathrm{Im}\lambda_5 > 0$$
$$4\lambda_b^2 - (\mathrm{Im}\lambda_5)^2 + \mathrm{Re}\lambda_5\mathrm{Im}\lambda_5 > 0$$

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These conditions were not considered in previous work

Benchmark points from previous analyses

Parameter	case A	case B	case C	case D	case E
$v_u = v_1$	245.925	245.936	245.951	245.917	245.948
$v_d = v_2$	6.086	5.595	4.921	6.387	5.077
$v_\phi = v_3$	-57.761	-36.470	-57.919	-30.746	-17.146
$\tan\beta = v_u/v_d$	40.410	43.957	49.977	38.503	48.441
λ_1	0.063	0.064	0.066	0.064	0.065
λ_2	-7.978	8.414	-2.000	2.948	10.382
λ_3	-6.344	-2.675	6.242	-1.724	-0.706
λ_4	1.859	2.158	-3.633	10.837	-2.796
λ_5	-11.384	-11.070	9.009	-11.460	-12.000
λ_6	2.888	1.228	0.866	1.351	1.324
λ_7	-0.282	-0.252	0.180	-0.298	-0.248
λ_8	-1.363	-1.346	-10.845	-11.510	7.033

A.Cárcamo Hernández, S.F.King, H.Lee, Phys. Rev. D 103, 115024 (2021)

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Benchmark points from previous analyses

Small vev for the singlet

Big values of tan beta

The scalar potential is not bounded from below

Almost non-perturbative quartic couplings

Their perturbativity condition is given by

$$g, y(\mathrm{NP}) < \sqrt{4\pi}$$

$$\lambda(\mathrm{NP}) < 4\pi$$

Parameter	case A	case B	case C	case D	case E
$v_u = v_1$	245.925	245.936	245.951	245.917	245.948
$v_d = v_2$	6.086	5.595	4.921	6.387	5.077
$v_\phi = v_3$	−57.761	−36.470	−57.919	−30.746	−17.146
$\tan\beta = v_u/v_d$	40.410	43.957	49.977	38.503	48.441
λ_1	0.063	0.064	0.066	0.064	0.065
λ_2	−7.978	8.414	−2.000	2.948	10.382
λ_3	−6.344	−2.675	6.242	−1.724	−0.706
λ_4	1.859	2.158	−3.633	10.837	−2.796
λ_5	−11.384	−11.070	9.009	−11.460	−12.000
λ_6	2.888	1.228	0.866	1.351	1.324
λ_7	−0.282	−0.252	0.180	−0.298	−0.248
λ_8	−1.363	−1.346	−10.845	−11.510	7.033

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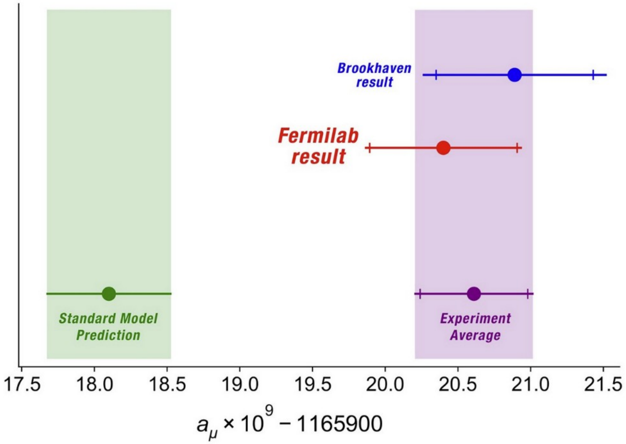
New Physics contributions to g-2

$$\Delta a_\mu = \sum_{i,j} \Bigg\{ -\frac{m_\mu^2}{16\pi^2 M_{\phi_i}^2} \left(|y_L^{ij}|^2 + |y_R^{ij}|^2 \right) \left[Q_j \mathcal{F}_1(x_{ij}) - Q_i \mathcal{G}_1(x_{ij}) \right]$$

$$- \frac{m_\mu M_{\psi_j}}{16\pi^2 M_{\phi_i}^2} \mathrm{Re}\left(y_L^{ij} y_R^{ij*} \right) \left[Q_j \mathcal{F}_2(x_{ij}) - Q_i \mathcal{G}_2(x_{ij}) \right] \Bigg\}$$

$$\Delta a_\mu = (2.49 \pm 0.48) \times 10^{-9}$$

Discrepancy is now at ~5.1 σ



Bennet et al, Phys. Rev. D 73 (2006) 072003 (hep-ex/0602035)
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$$\left. - \frac{m_\mu M_{\psi_j}}{16\pi^2 M_{\phi_i}^2} \mathrm{Re}\left(y_L^{ij} y_R^{ij*} \right) \left[Q_j \mathcal{F}_2(x_{ij}) - Q_i \mathcal{G}_2(x_{ij}) \right] \right\}$$

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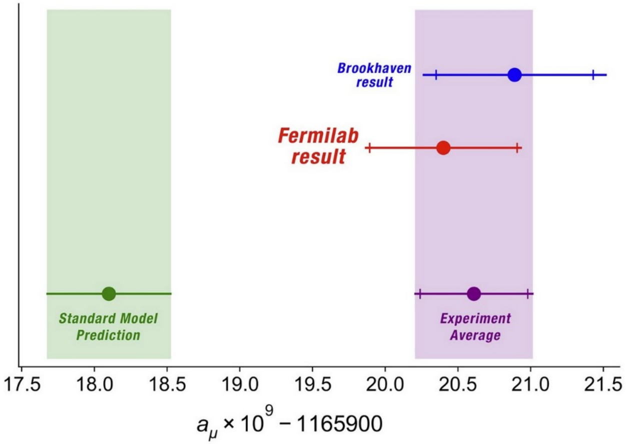
Lattice
???



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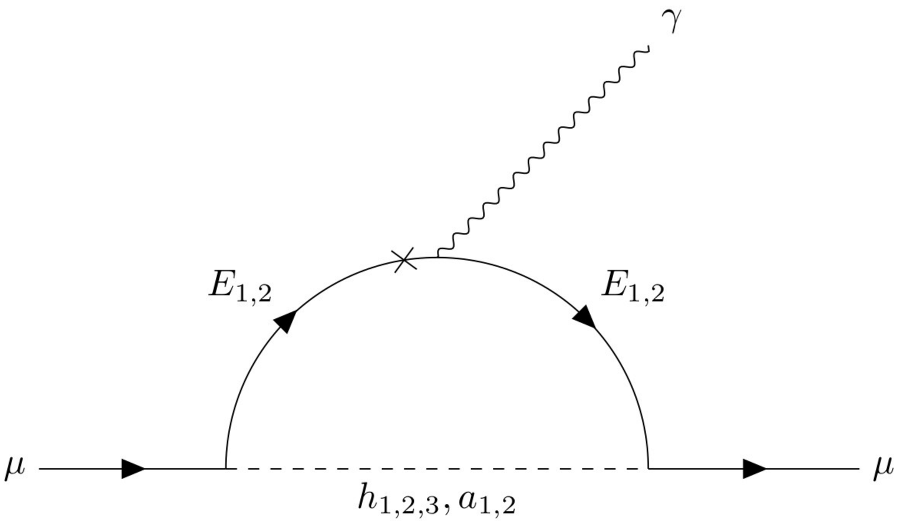

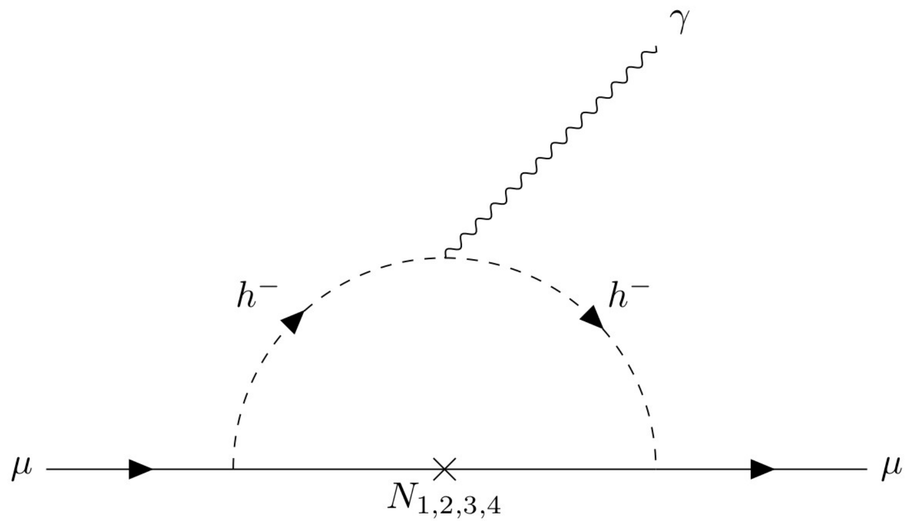

Perturbativity and g-2

We define the cutoff energy for the model by requiring that any New Physics wrt the model is at such an energy scale that the corrections to g-2 are negligible.

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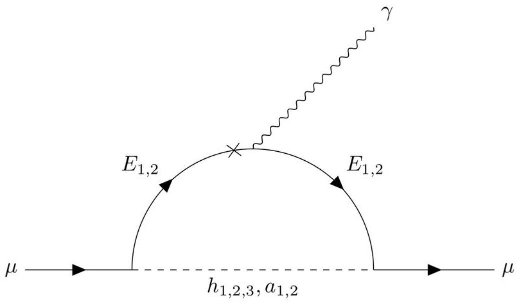

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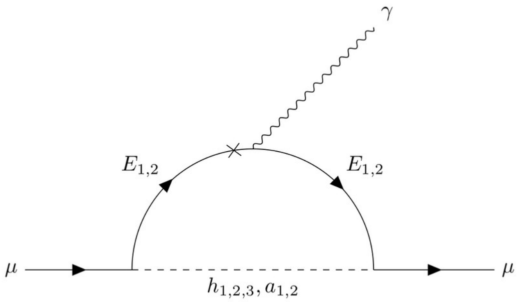

By requiring that such correction is smaller than 3σ and in the most pessimistic scenario

$$y_L(\Lambda) = y_R(\Lambda) = \sqrt{4\pi}$$

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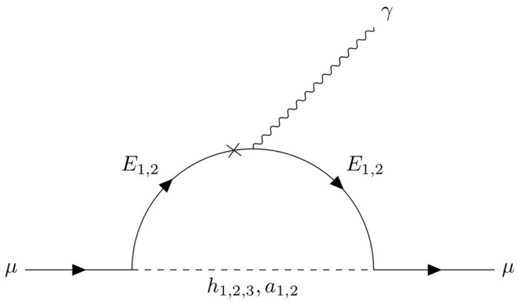

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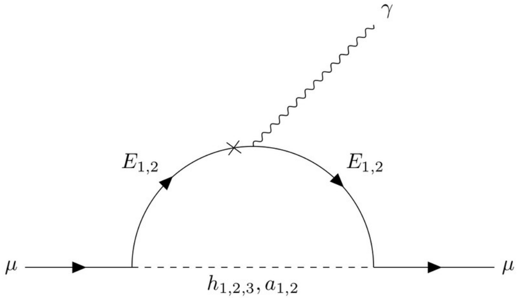

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$$\cancel{g, y(\text{NP}) < \sqrt{4\pi}} \qquad g, y(\text{NP}) \lesssim 1$$

$$\cancel{\lambda(\text{NP}) < 4\pi} \qquad \lambda(\text{NP}) \lesssim 2$$

All benchmark point from previous works are this way excluded.

Contributions to $\Delta a_\mu \times 10^9$							
Charged scalars				CP-even scalars			
Loop	BP1	BP2	BP3	Loop	BP1	BP2	BP3
$h^\pm, N_{1,2}$				h_1, E_1			
$h^\pm, N_{3,4}$				h_1, E_2			
$h^\pm, N_{\rm tot}$				h_2, E_1			
CP-odd scalars				h_2, E_2			
a_1, E_1				h_3, E_1			
a_1, E_2				h_3, E_2			
a_2, E_1				$h, E_{\rm tot}$			
a_2, E_2				Total			
$a, E_{\rm tot}$				Δa_μ			

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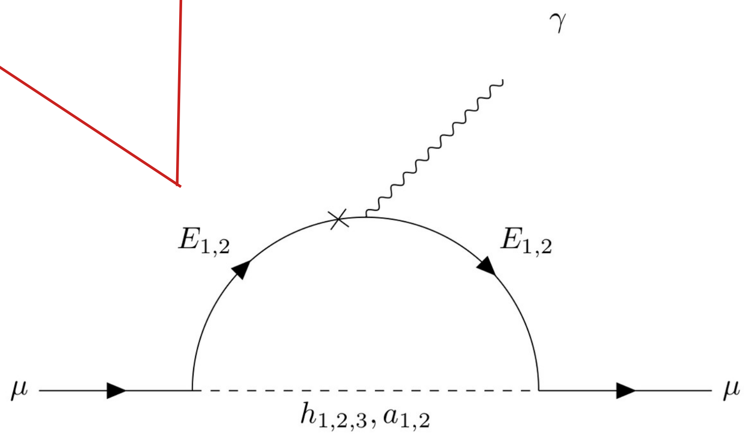
a_2, E_2				Total			
a, E_{tot}				Δa_μ			

Contributions given by these diagrams have been computed already in previous works



New Physics contributions to g-2

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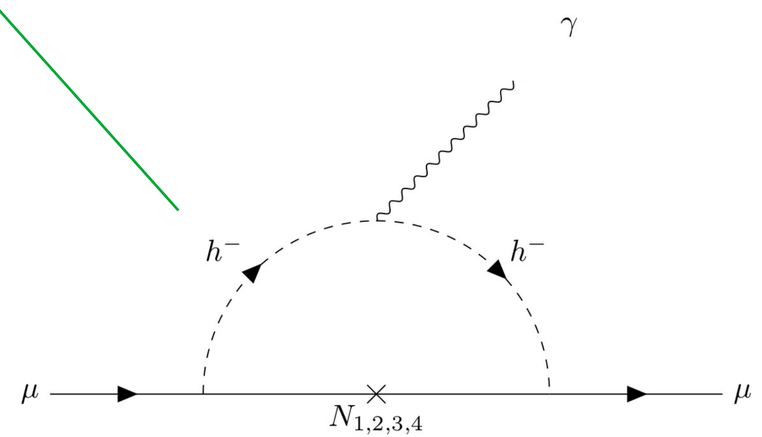
a, E_{tot}				Δa_μ			

Contributions given by this diagram have **not** been considered in previous works



New Physics contributions to 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

The deviation from the experimental measurement of g-2 can be explained within this model.

The main contribution to g-2 in mediated by **charged scalars** and **neutrinos**!

New Physics Spectra

New Physics Spectra

VL Quarks

$U_1 \rightarrow \sim 1500$ GeV
$D_1 \rightarrow \sim 1500$ GeV
$U_2 \rightarrow \sim 1700\text{-}1900$ GeV
$D_2 \rightarrow \sim 2900\text{-}3600$ GeV

VL Leptons

$N_{1,2} \rightarrow \sim 200$ GeV
$N_{3,4} \rightarrow \sim 500\text{-}600$ GeV
$E_1 \rightarrow \sim 500\text{-}600$ GeV
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CP-Even Scalars

$h_1 \rightarrow 125$ GeV
$h_2 \rightarrow \sim 400$ GeV
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Can be tested in Run 3

LHC Bounds on vector-like fermions

Leptons

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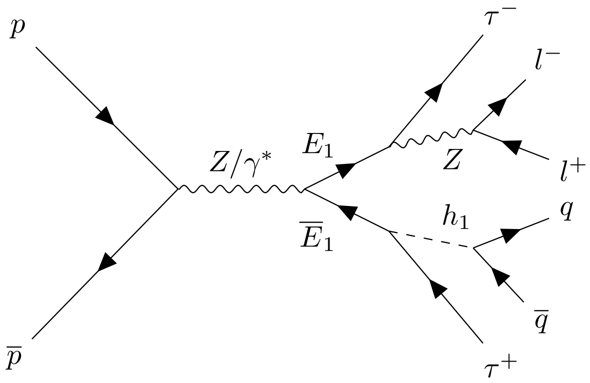

ATLAS: JHEP 07, 118 (2023)
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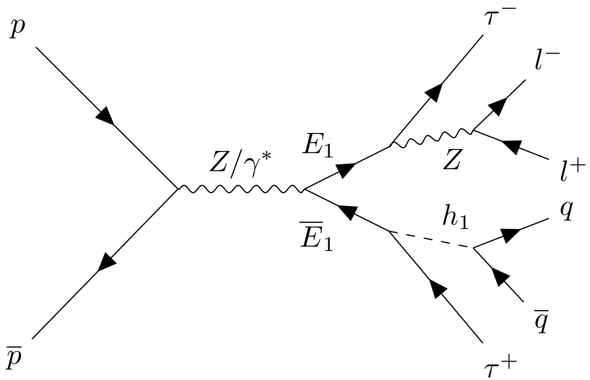

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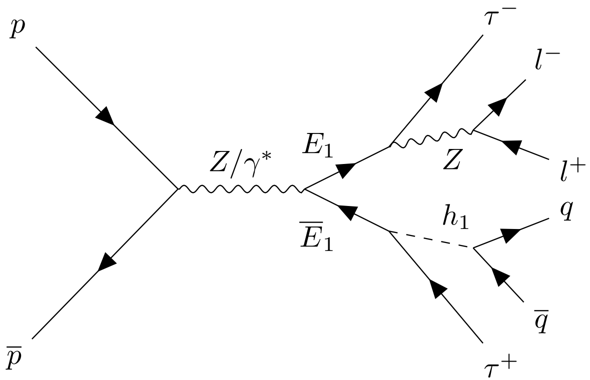

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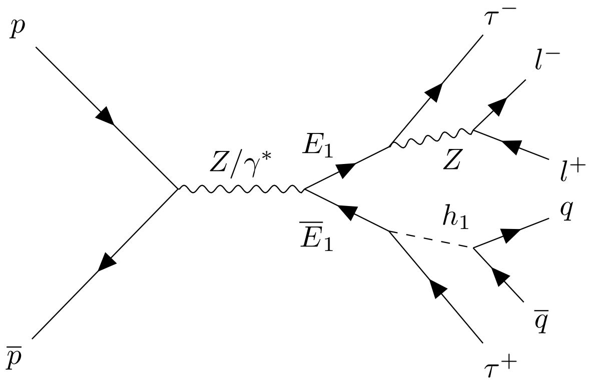

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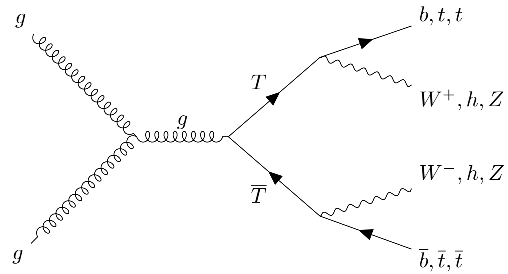

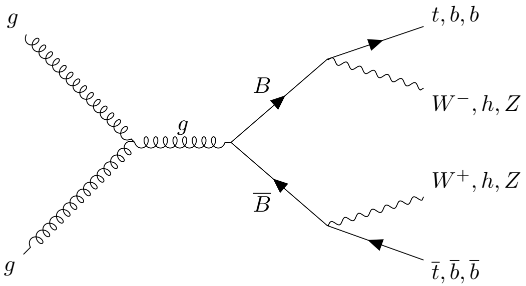

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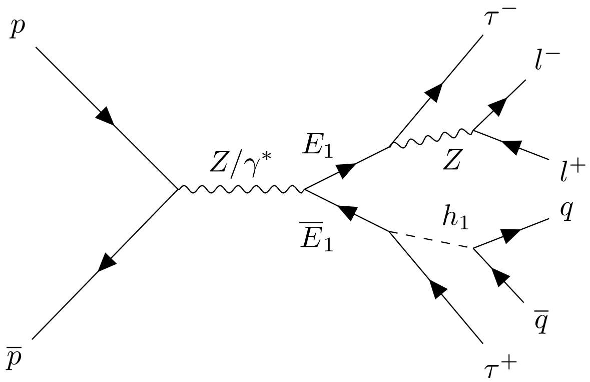

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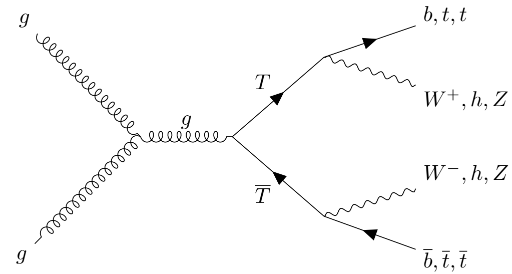
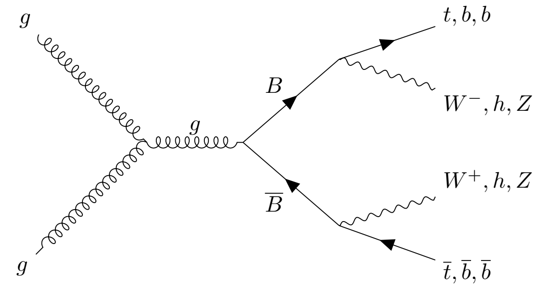




ATLAS: Eur. Phys. J. C 83, 719 (2023)
CMS: JHEP 07, 020 (2023)

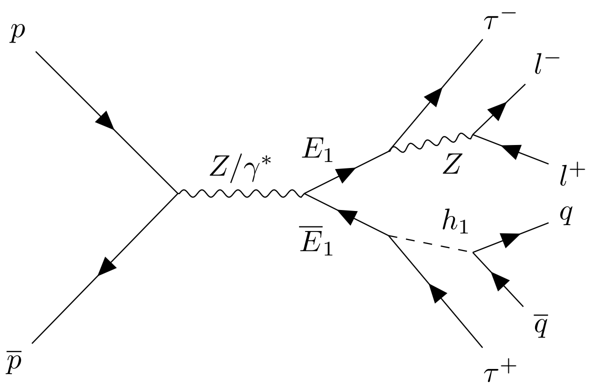
The x-section is one order of magnitude smaller than the current bounds.

LHC Bounds on vector-like fermions

Leptons

Our leptons decay predominantly to muons, but there are **no** dedicated experimental analysis.

The best we can do is study:



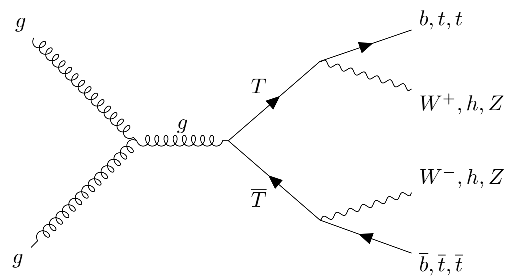
ATLAS: JHEP 07, 118 (2023)
CMS: Phys. Rev. D 100, 052003 (2019)

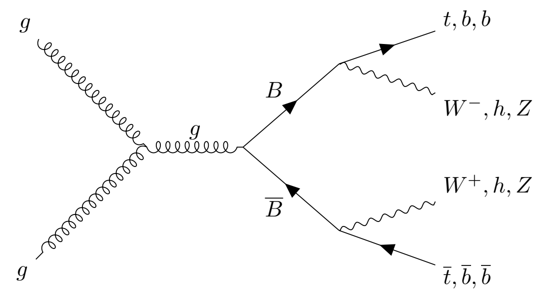
BR(LL→ττ) < 10% and x-section is 3-4 orders of magnitude **smaller** than current bounds.

Can **not** be tested in Run 3

Quarks

Two possible channels can be studied:





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

The x-section is one order of magnitude smaller than the current bounds.

Can be tested in Run 3

Conclusions

- I have discussed a NP model which can explain SM fermion's **mass generation** (and mixings) in a completely new way (SM-like interactions are not allowed).

- We have **re-assessed** findings from previous works. The main result is a thorough study of the **perturbativity** of the model, investigated by requiring that the observable do not get corrections from possible UV completions.

- When imposing conditions on the parameter space (SM masses and couplings, vacuum stability, perturbativity) the number of free parameters gets drastically reduced, preventing the model from having a too big parameter space.

- We have presented (c.f. paper) **three benchmark points** which accommodate all the physical requirements and explain the deviation in the muon g-2.

- Incidentally, the perturbativity of the benchmark points is guaranteed up to a much higher energy scale (1000 TeV) than the theoretical value (50 TeV).

- The main contribution to **g-2** is the loop with **neutrino** and **charged scalar**.

- The benchmark points can be **tested** at the LHC: discovery/exclusion.

CKM Mixing Matrix

Reduced CKM matrix

$$\mathrm{V}_{\mathrm{CKM}}^{3\times 3} \approx \begin{pmatrix} 1 - x_{ud}^2/2 & x_{ud} & x_{ud}x_d \\ -x_{ud} & 1 - x_{ud}^2/2 & x_d - x_u \\ -x_u x_{ud} & x_u - x_d & 1 \end{pmatrix}$$

$$x_d = \frac{y_{24}^d x_{43}^d M_4^Q}{y_{43}^d x_{34}^Q M_4^d} = 0.017 \qquad x_u = \frac{y_{24}^u x_{43}^u M_4^Q}{y_{43}^u x_{34}^Q M_4^u} \approx -0.023 \qquad x_{ud} = \frac{y_{14}^d}{y_{24}^d} \approx 0.22$$

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

With only 1 VL family it is not possible to fit all the elements of the CKM matrix!

Mass generation for fermions

$$M_{U_1} \approx \sqrt{(M_4^Q)^2 + \frac{1}{2}(v_\phi x_{34}^Q)^2 - \frac{(M_4^Q y_{43}^u v_u)^2}{(x_{34}^Q v_\phi)^2 + 2(M_4^Q)^2}}$$

$$M_{U_2} \approx \sqrt{(M_4^u)^2 + \frac{1}{2}(v_\phi x_{43}^u)^2 + \frac{1}{2}(v_\phi x_{42}^u)^2 + \frac{2(M_4^u y_{43}^u v_u)^2}{2(M_4^u)^2 + (v_\phi x_{43}^u)^2 + (v_\phi x_{42}^u)^2}}$$

$$M_{D_1} \approx \sqrt{(M_4^Q)^2 + \frac{1}{2}(v_\phi x_{34}^Q)^2}$$

$$M_{D_2} \approx \sqrt{(M_4^d)^2 + \frac{1}{2}(v_\phi x_{43}^d)^2 + \frac{1}{2}(v_\phi x_{42}^d)^2}$$

$$M_{E_1} \approx \sqrt{(M_4^L)^2 + \frac{1}{2}(v_\phi x_{34}^L)^2}$$

$$M_{E_2} \approx \sqrt{(M_4^e)^2 + \frac{1}{2}(v_\phi x_{43}^e)^2 + \frac{1}{2}(v_\phi x_{42}^e)^2}$$

$$M_{N_1} = M_{N_2} \approx M_4^\nu$$

$$M_{N_3} = M_{N_4} \approx \sqrt{(M_4^L)^2 + \frac{1}{2}(v_\phi x_{34}^L)^2}$$

Parameter Space

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	$\pm\,[1200, 4000]$

Minimization of a χ^2 function
to determine benchmark points.

SM masses, CKM elements, g-2

Benchmark Points

Scalar sector							
	BP1	BP2	BP3		BP1	BP2	BP3
$\tan\beta$	13	8	12	λ_1	0.258	0.258	0.258
v_u	245.3	244.3	245.2	λ_2	0.514	0.153	0.623
v_d	18.9	30.5	20.4	λ_3	0.257	0.260	0.256
v_ϕ	1015	1077	1012	λ_4	0.552	0.304	0.167
μ_u^2	-7.8×10^3	-6.6×10^3	-7.6×10^3	λ_5	-0.039	-0.072	-0.061
μ_d^2	-8.2×10^3	-8.6×10^4	-3.4×10^4	λ_6	0.370	0.487	0.663
μ_ϕ^2	-4.9×10^4	-9.4×10^4	-2.3×10^5	λ_7	0.001	0.002	0.002
$\mu_{\rm sb}^2$	1.4×10^5	1.9×10^5	1.1×10^5	λ_8	0.254	0.423	0.417

Mass parameters							
	BP1	BP2	BP3		BP1	BP2	BP3
M_4^u	-1317	1405	1334	M_4^e	-517	-575	533
M_4^d	-3644	3068	-2882	M_4^ν	204	-212	217
M_4^Q	-1384	1443	1322	M_4^L	-206	-222	-202

Benchmark Points

Quark sector				Lepton sector			
	BP1	BP2	BP3		BP1	BP2	BP3
y^u_{24}	-0.051	-0.049	0.050	y^e_{24}	0.028	-0.015	0.022
y^u_{34}	-0.980	1.185	-1.024	y^e_{34}	-0.895	0.612	0.790
x^Q_{34}	0.924	-0.842	-0.877	x^L_{34}	0.616	-0.729	0.724
y^u_{43}	1.382	1.093	-1.337	y^e_{43}	-0.223	0.144	-0.191
x^u_{42}	0.550	0.821	-0.595	x^e_{42}	0.156	0.165	0.188
x^u_{43}	1.286	1.261	1.263	x^e_{43}	-0.168	0.228	-0.205
y^d_{14}	-0.022	0.035	0.026	y^ν_{14}	-2×10^{-11}	5×10^{-11}	3×10^{-11}
y^d_{24}	0.096	0.151	-0.113	y^ν_{24}	3×10^{-11}	8×10^{-12}	6×10^{-11}
y^d_{34}	-0.684	0.274	0.267	y^ν_{34}	-5×10^{-11}	9×10^{-11}	9×10^{-11}
y^d_{43}	-0.672	-0.489	0.656	y'^ν_{14}	-0.824	-0.674	-0.674
x^d_{42}	-0.371	-0.110	0.225	y'^ν_{24}	-0.895	-0.874	-0.896
x^d_{43}	-0.160	0.072	-0.127	y'^ν_{34}	0.701	0.744	-0.812

Mass Spectrum

SM fermions							
	BP1	BP2	BP3		BP1	BP2	BP3
m_c	1.262	1.282	1.259	m_μ	0.110	0.110	0.110
m_t	172.7	172.8	172.6	m_τ	1.864	1.756	1.765
m_s	0.089	0.093	0.091	m_{ν_2} $[10^{-10}]$	4.659	6.587	0.252
m_b	4.169	4.196	4.175	m_{ν_3} $[10^{-10}]$	8.253	18.38	20.95
NP fermions							
Quark sector				Lepton sector			
	BP1	BP2	BP3		BP1	BP2	BP3
M_{U_1}	1495	1561	1440	M_{E_1}	487	596	554
M_{U_2}	1708	1842	1704	M_{E_2}	543	615	570
M_{D_1}	1534	1579	1464	$M_{N_{1,2}}$	205	214	218
M_{D_2}	3655	3070	2888	$M_{N_{3,4}}$	488	598	556
Scalars							
	BP1	BP2	BP3		BP1	BP2	BP3
M_{h_1}	125	125	125	M_{a_1}	362	411	433
M_{h_2}	362	412	435	M_{a_2}	532	614	469
M_{h_3}	617	752	824	$M_{h^\pm}$	384	423	440