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# Muon and electron $g - 2$ in a $Z'$ model with vector-like fermions

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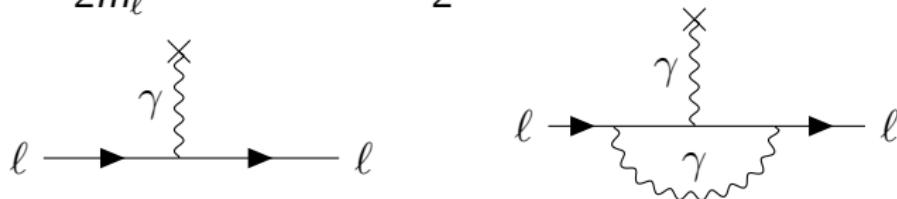
18 Dec 2019

- ▶ Motivation
- ▶ Vector-like fermion and  $Z'$  model
- ▶ This work
- ▶ Predictions for  $\Delta a_\mu$  and  $\Delta a_e$
- ▶ Numerical analysis
- ▶ Conclusions and outlook

# Motivation

Leptons have magnetic moments along their spin direction

$$\vec{\mu}_\ell = g_\ell \frac{Q}{2m_\ell} \vec{s}, \quad a_\ell = \frac{g_\ell - 2}{2}, \quad \Delta a_\ell = a_{\text{exp}} - a_{\text{SM}}$$



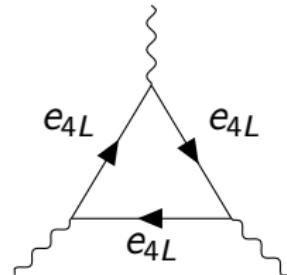
- ▶  $\Delta a_\mu$ : Longstanding tension between SM and BNL measurement<sup>[1]</sup>
$$\Delta a_\mu = (26.1 \pm 8.0) \times 10^{-10} \sim 3.5\sigma \text{ from SM}$$
- ▶  $\Delta a_e$ : Tension between SM and recent measurement from Caesium<sup>[2]</sup>
$$\Delta a_e = (-0.88 \pm 0.36) \times 10^{-12} \sim 2.5\sigma \text{ from SM}$$
- ▶ Attempt to simultaneously explain  $\Delta a_\mu$  and  $\Delta a_e$

<sup>[1]</sup>G. W. Bennett et al. [Muon g-2 Collaboration], Phys. Rev. D 73, 072003 (2006)

<sup>[2]</sup>R. H. Parker et. al., Science 360, 191 (2018)

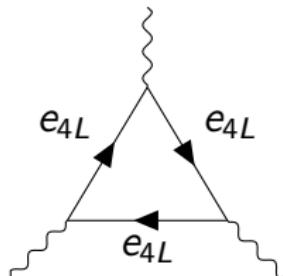
# Vector-like fermions

- ▶ Minimal idea: 4th chiral family of fermions e.g.  $e_{4L}$ ,  $\nu_{4L}$
- ▶ !!! Problem !!! chiral gauge anomalies  $\implies$



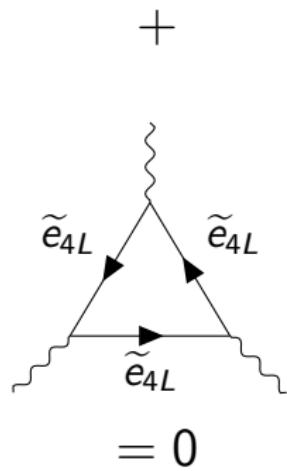
# Vector-like fermions

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- ▶ !!! Problem !!! chiral gauge anomalies  $\implies$



- ▶ Need a further family e.g.  $\tilde{e}_{4L}$ ,  $\tilde{\nu}_{4L}$  of opposite chirality
- ▶ Anomalies cancel if quantum numbers identical!

Models with such vector-like fermions are **necessarily anomaly-free**



# Vector-like fermions and $U(1)'$

Model gauge group:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$$

Field content:

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
SM fermions	#	#	#	0
$L_{L4}$	<b>1</b>	<b>2</b>	-1/2	$q_{L4}$
$e_{R4}$	<b>1</b>	<b>1</b>	-1	$q_{L4}$
$\tilde{L}_{R4}$	<b>1</b>	<b>2</b>	-1/2	$q_{L4}$
$\tilde{e}_{L4}$	<b>1</b>	<b>1</b>	-1	$q_{L4}$
$\phi_L$	<b>1</b>	<b>1</b>	0	$-q_{L4}$
$\phi_e$	<b>1</b>	<b>1</b>	0	$-q_{L4}$

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NB: In high-energy theory, SM fermions uncoupled from  $U(1)'$

# Vector-like fermions and $U(1)'$

Possible Lagrangian terms:

$$\mathcal{L} \supset y_4^{(e)} \bar{L}_{L4} H e_{R4} + \sum_{i=1}^3 x_i^{(L)} \phi_L \bar{L}_{Li} \tilde{L}_{R4} + \sum_{i=1}^3 x_i^{(e)} \phi_e \bar{\tilde{e}}_{L4} e_{Ri} + M_4^L \bar{L}_{L4} \tilde{L}_{R4} + M_4^E \bar{\tilde{e}}_{L4} e_{R4}$$

$\phi$ s acquire VEVs to break  $U(1)'$  at TeV scale. SM Higgs breaks EW symmetry as normal

$$\mathcal{L} \supset M_4^C \bar{L}_{L4} H e_{R4} + M_4^L \bar{L}_{L4} \tilde{L}_{R4} + M_4^E \bar{\tilde{e}}_{L4} e_{R4} + \text{mixing terms } (\phi \text{ interactions})$$

# Massive $Z'$ couplings

Initially, SM fermions uncoupled from  $Z'$

$$\mathcal{L} \supset g' Z'_\mu (\bar{L}_L D_L \gamma^\mu L_L + \bar{E}_R D_E \gamma^\mu E_R)$$

Interaction basis (pure flavour states):

$$L_L = \begin{pmatrix} (e_L, \nu_e) \\ (\mu_L, \nu_\mu) \\ (\tau_L, \nu_\tau) \\ (e_{L4}, \nu_{L4}) \end{pmatrix}, \quad E_R = \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \\ e_{R4} \end{pmatrix}, \quad D_L = \text{diag}(0, 0, 0, q_{L4})$$

Transform to mass basis  $\implies$ :

$$V_{L_L, e_R} = \begin{pmatrix} \cos \theta_{14}^{L,R} & 0 & 0 & \sin \theta_{14}^{L,R} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin \theta_{14}^{L,R} & 0 & 0 & \cos \theta_{14}^{L,R} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \theta_{24}^{L,R} & 0 & \sin \theta_{24}^{L,R} \\ 0 & 0 & 1 & 0 \\ 0 & -\sin \theta_{24}^{L,R} & 0 & \cos \theta_{24}^{L,R} \end{pmatrix}$$

# Low-energy couplings

$$(g_{L,R})_{Z'\mu\mu} = g' q_{L_4} (\sin \theta_{24L,R})^2$$

$$(g_{L,R})_{Z'ee} = g' q_{L_4} (\cos \theta_{24L,R} \sin \theta_{14L,R})^2$$

$$(g_{L,R})_{Z'\mu e} = g' q_{L_4} (\cos^2 \theta_{24L,R} \sin \theta_{14L,R})$$

$$(g_{L,R})_{Z'\mu E} = g' q_{L_4} (\cos \theta_{24L,R} \cos \theta_{14L,R} \sin \theta_{24L,R})$$

$$(g_{L,R})_{Z'eE} = g' q_{L_4} (\cos \theta_{14L,R} \cos^2 \theta_{24L,R} \sin \theta_{14L,R})$$

For simplicity, set  $g' q_{L_4} = 1$

Couplings can be expressed in terms of  $\sin^2 \theta_{24L,R}$  and  $\sin^2 \theta_{14L,R}$

- ▶ Attempt to simultaneously explain  $\Delta a_\mu$  and  $\Delta a_e$
- ▶ Restricted by decays  $\mu \rightarrow e\gamma$  and  $\nu_\mu \gamma^* \rightarrow \nu_\mu \mu^+ \mu^-$ :

$$\text{BR}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$$

Non-observation at MEG  
experiment<sup>[3]</sup>

$$\frac{(g_L)_{\mu\mu}^2}{M_{Z'}^2} \lesssim \frac{1}{(370\text{GeV})^2}$$

SMEFT global fit analysis<sup>[4]</sup>

## Minimal Parameter Space

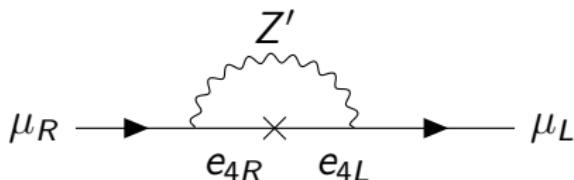
$$M_{Z'}, \quad M_4^L, \quad M_4^C, \quad \sin^2\theta_{24L,R}, \quad \sin^2\theta_{14L}$$

<sup>[3]</sup> MEG Collaboration (A.M. Baldini et. al.) Eur.Phys.J. **C76** (2016) no.8, 434

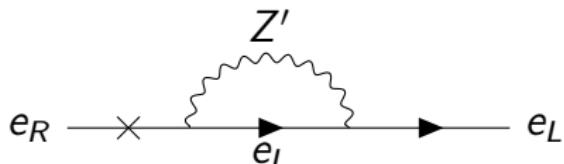
<sup>[4]</sup> A. Falkowski, M. González-Alonso, K. Mimouni JHEP 1708 (2017) 123

# Predictions for observables

$\Delta a_\mu$ :



$\Delta a_e$ :



$$\Delta a_\mu^{Z'} = -\frac{m_\mu^2}{8\pi^2 M_{Z'}^2} \left[$$

$$\text{Re } ((g_L)_{\mu E} (g_R^*)_{\mu E}) \frac{M_4^C}{m_\mu} G(\left(\frac{M_4^L}{m_\mu}\right)^2) +$$

$$\text{Re } ((g_L)_{\mu e} (g_R^*)_{\mu e}) \frac{m_e}{m_\mu} G(\left(\frac{m_e}{m_\mu}\right)^2) + \dots \right]$$

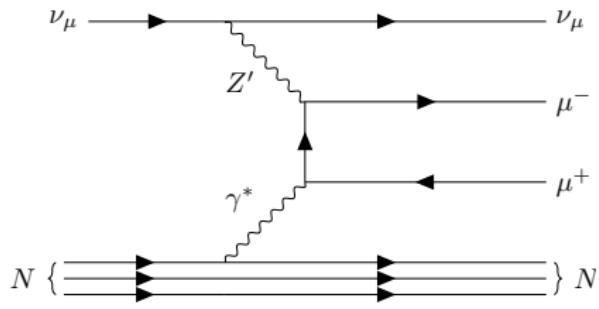
$$\Delta a_e^{Z'} = -\frac{m_e^2}{8\pi^2 M_{Z'}^2} \left[$$

$$(|(g_L)_{ee}|^2 + |(g_R)_{ee}|^2) F(\left(\frac{m_e}{m_\mu}\right)^2)$$

$$+ \dots \right]$$

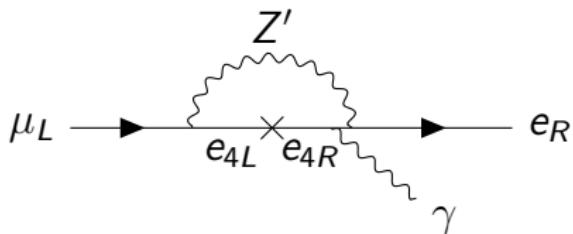
# Predictions for observables

Neutrino trident production:



Direct constraint on  $(g_L)_{\mu\mu}/M_{Z'}$  from SMEFT

$\mu \rightarrow e\gamma$ :



$$\text{BR}(\mu \rightarrow e\gamma) = \frac{\alpha}{1024\pi^4} \frac{m_\mu^5}{M_{Z'}^4 \Gamma_\mu} \left[ \frac{M_4^C}{m_\mu} (g_R)_{eE} (g_L)_{\mu E} G\left(\left(\frac{M_4^L}{m_\mu}\right)^2\right) + \dots \right]$$

- ▶ Attempt to simultaneously explain  $\Delta a_\mu$  and  $\Delta a_e$
- ▶ Restricted by decays  $\mu \rightarrow e\gamma$  and  $\nu_\mu \gamma^* \rightarrow \nu_\mu \mu^+ \mu^-$ :

## Minimal Parameter Space

$$M_{Z'}, \quad M_4^L, \quad M_4^C, \quad \sin^2\theta_{24L,R}, \quad \sin^2\theta_{14L}$$

- ▶ Have expressions for phenomena ∴
- ▶ Fix some parameters  $\implies$  find allowed/excluded regions
- ▶ Full parameter space  $\implies$  random scan, examine points

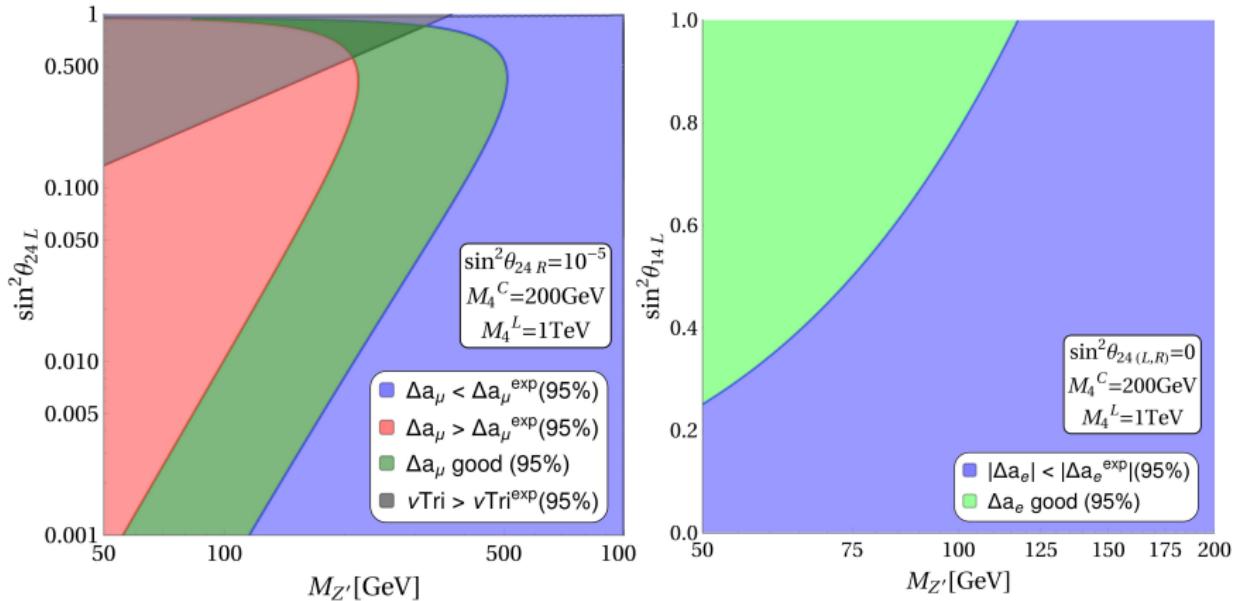
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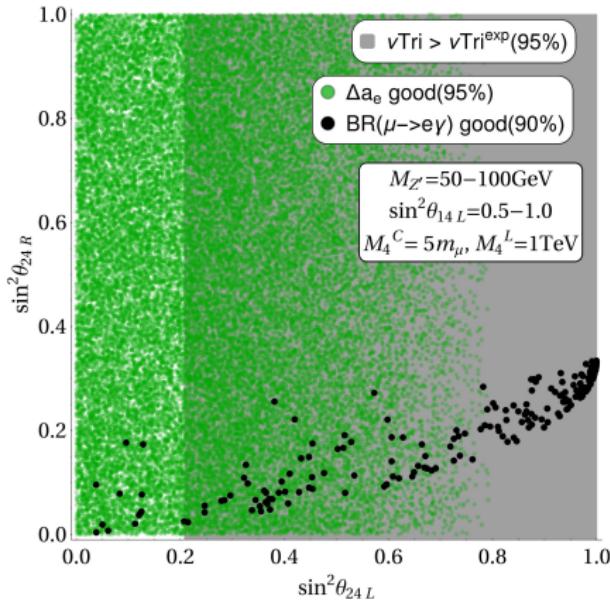
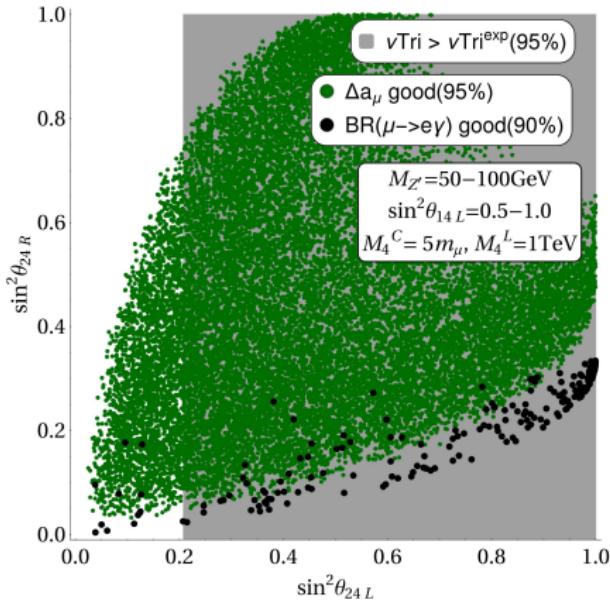
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# Analysis: Large $M_4^C$



- Terms with  $M_4^C$  enhancement dominate

# Analysis: Small $M_4^C$



- Points look good, seems to be overlap, *but...*

# Viable points (low $\sin^2 \theta_{24L}$ )

Parameter		Observable		
$\sin^2 \theta_{24L}$	$\sin^2 \theta_{24R}$	$\text{BR}(\mu \rightarrow e\gamma)$	$\Delta a_e$	$\Delta a_\mu$
0.12	0.04	$1.44 \times 10^{-13}$	$-3.27 \times 10^{-13}$	$-5.09 \times 10^{-10}$
0.08	0.08	$2.95 \times 10^{-13}$	$-5.08 \times 10^{-13}$	$-1.32 \times 10^{-9}$
0.08	0.08	$4.73 \times 10^{-14}$	$-3.24 \times 10^{-13}$	$-7.90 \times 10^{-10}$
0.06	0.008	$1.81 \times 10^{-13}$	$-3.85 \times 10^{-13}$	$-1.60 \times 10^{-10}$
0.10	0.18	$4.93 \times 10^{-16}$	$-2.02 \times 10^{-13}$	$-1.13 \times 10^{-9}$
0.12	0.04	$3.51 \times 10^{-13}$	$-2.06 \times 10^{-13}$	$-2.95 \times 10^{-10}$
0.11	0.02	$1.01 \times 10^{-13}$	$-2.19 \times 10^{-13}$	$-2.11 \times 10^{-10}$
0.04	0.10	$4.72 \times 10^{-13}$	$-3.15 \times 10^{-13}$	$-8.63 \times 10^{-10}$
0.04	0.004	$8.78 \times 10^{-14}$	$-3.27 \times 10^{-13}$	$-7.88 \times 10^{-11}$
0.05	0.02	$4.56 \times 10^{-14}$	$-1.88 \times 10^{-13}$	$-1.20 \times 10^{-10}$
0.13	0.04	$5.63 \times 10^{-14}$	$-1.63 \times 10^{-13}$	$-2.67 \times 10^{-10}$
0.13	0.17	$4.52 \times 10^{-16}$	$-1.91 \times 10^{-13}$	$-1.09 \times 10^{-9}$

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## Summary:

- ▶ VLF and  $U(1)'$  model can explain either  $\Delta a_\mu$  or  $\Delta a_e$ , but not both simultaneously (at 95% CL)
- ▶ Remains good candidate for other lepton phenomena - look forward to new results and theory update

## Future work:

- ▶ Extension of current work  $\rightarrow (g - 2)$  calculation with additional scalars
- ▶ Collider phenomenology and search for 'smoking gun' signatures

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**Thanks for your attention**