JRJC - La Rochelle

Solving $(g-2)_\ell$ with a new light gauge boson

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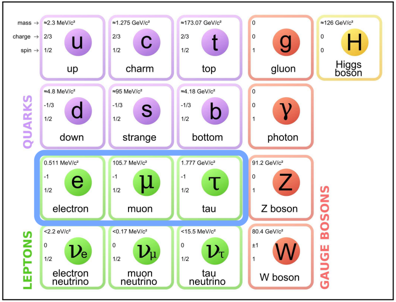
- Describes particles and their interactions
- Successfully tested
  Good experimental predictions



But cannot account for some observations:

Neutrino masses, Dark Matter, baryon asymmetry of the Universe

And numerous **tensions** between theory and observation:

$(g-2)_\ell$, Cabibbo-angle anomaly, B meson anomalies, ...

$\Longrightarrow$ Need **New Physics** (beyond SM)

Magnetic moment $\rightarrow$ Measure of particle's tendency to align with a magnetic field

$$\boxed{\vec{\mu}_\ell = g_\ell \frac{e}{2m_\ell}\vec{s}}$$

$\vec{s}$, m_ℓ: spin and mass of the lepton
g_ℓ Landé factor (characterizes the "strength" of the lepton coupling to a magnetic field)

From Dirac equation : $g_\ell \equiv g_{\text{Dirac}} = 2$

But quantum corrections need to be taken into account!

Electromagnetic lepton current (external magnetic field)

$$\mathcal{J}_\mu = \bar{\ell}(p')\left[\gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_\ell}F_2(q^2) + \gamma_5\frac{i\sigma_{\mu\nu}q^\nu}{2m_\ell}F_3(q^2) + \gamma_5(q^2\gamma_\mu - \not{q}q_\mu)F_4(q^2)\right]\ell(p)$$

$$g_\ell = 2(F_1(0) + F_2(0))$$

SM tree-level : $F_1(0) = 1$ and $F_2(0) = F_{3,4}(0) = 0$

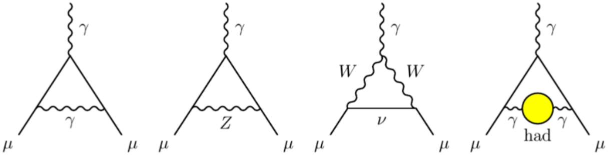
Leads to $g_\ell = 2 = g_{\text{Dirac}}$

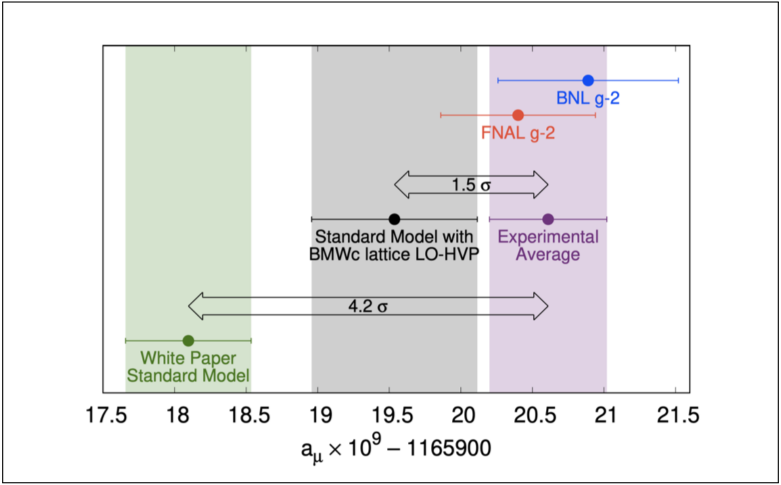
Higher order corrections from $F_2(0)$ at loop level
$\Longrightarrow$ Define **anomalous magnetic moment**

$$\boxed{a_\ell \equiv \frac{g_\ell - g_{\text{Dirac}}}{g_{\text{Dirac}}} = \frac{g_\ell - 2}{2} = F_2(0)}$$

First correction in 1948 (QED NLO) : $a_\ell = \dfrac{\alpha}{2\pi}$

Now : $a_\ell = {a_\ell}^{\text{QED}} + {a_\ell}^{\text{EW}} + {a_\ell}^{\text{had}}$
QED contributions: at 5-loop
EW at 2-loop
(non perturbative) QCD in hadronic light-by-light scattering, hadronic vacuum polarization





$$\Delta a_\mu = 251(59) \times 10^{-11}$$

$\Longrightarrow$ Need **New Physics** to account for this discrepancy

What about the electron ?

From **scaling of effective dipole operators**, expect :

$$\frac{\Delta a_e}{\Delta a_\mu} \sim \frac{m_e}{m_\mu} \sim 5 \times 10^{-3}$$

From **symmetry arguments** would expect :

$$\frac{\Delta a_e}{\Delta a_\mu} \sim \frac{m_e^2}{m_\mu^2} \sim 2.5 \times 10^{-5}$$

But Δa_e from **precise measurement of** α_e with **Cs** atoms

$$\Delta a_e{}^{\mathrm{Cs}} \sim (-0.88 \pm 0.36) \times 10^{-12}$$

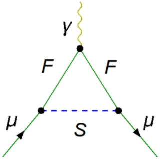
Leading to $\dfrac{\Delta a_e}{\Delta a_\mu} \sim -3 \times 10^{-4}$

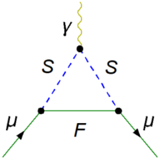
$\Longrightarrow$ **2.5σ tension**, "wrong" sign **and** order of magnitude

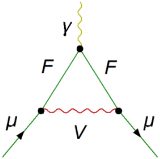
- Single field extension of the SM
  - $\boldsymbol{Z'}$ (BSM "cousin" of SM Z)
  - Dark photon
  - Two-Higgs-Doublet Model
  - Scalar Leptoquark

- Two or Three-field extension of the SM
  - Vector-like leptons
  - $\#$ Scalar(s) $+$ $\#$ Fermion(s)

- Supersymmetry

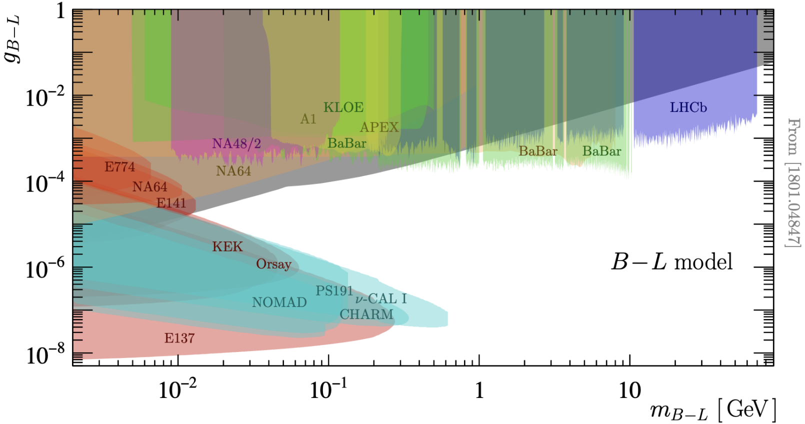






From [2104.03691]

Minimal Z' model



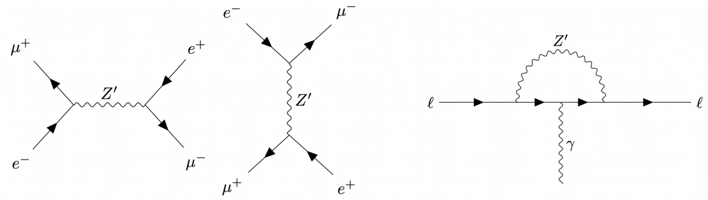
Constraints on Z' parameters (mass and coupling) from $U(1)_{B-L}$

Can **evade** these bounds considering **Flavor Violating** coupling to leptons!

Extend the SM content with one new (light) **neutral gauge boson Z'**

$$\mathcal{L} = Z'_\mu \left[\bar{\ell}_i \gamma^\mu (g^{ij}_{\ell L} P_L + g^{ij}_{\ell R} P_R) \ell_j + \bar{\nu_\alpha} \gamma^\mu (g^{\alpha\beta}_{\nu L} P_L) \nu_\beta \right] + \text{H.c.}$$

- Expect chiral enhancement $\Longrightarrow$ **sizeable contributions** to $(g-2)_\ell$
- Only coupling to **leptons** to avoid hadronic constraints
- Only **Flavor Violating** couplings to evade constraints from direct searches and EW precision observables



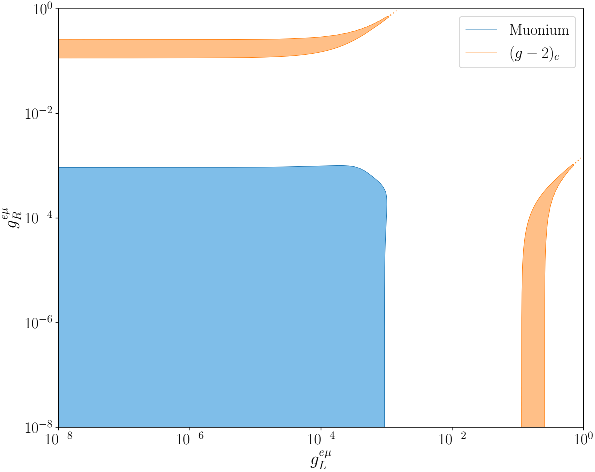
Muonium oscillations:

- $\mathrm{Mu} = \mu^+ e^-$ bound state used to test the SM
- In models with **cLFV**, can oscillate into antimuonium $\overline{\mathrm{Mu}} = \mu^- e^+$ (similar to neutral meson oscillation)
- In this Z' model, contributions **@ tree-level!**

$\Rightarrow$ Stringent constraints expected

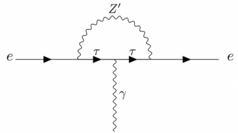
Can Z' account for $(g-2)_e$ and comply with $\mathrm{Mu} - \overline{\mathrm{Mu}}$ bounds ?

Constraints on $e\mu$ couplings

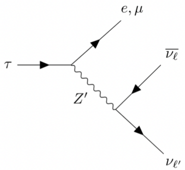


$\Longrightarrow$ Mu oscillations **exclude** $(g-2)_e$ via $\boldsymbol{e\mu}$ couplings

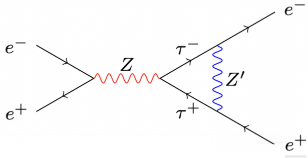
- **But!** $(g-2)_e$ induced by τ in the loop



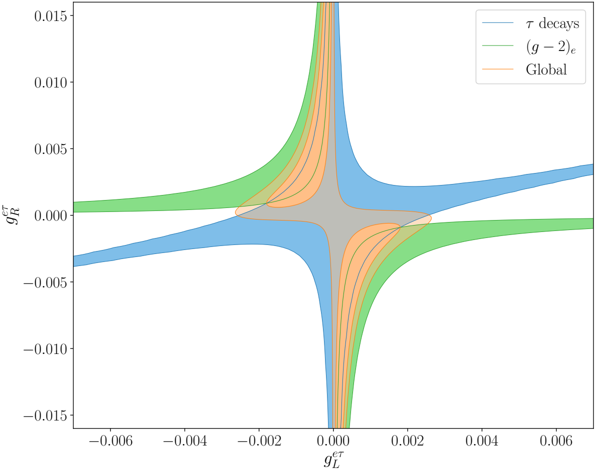
- $\boldsymbol{\tau}$ decay : $\tau \to e\overline{\nu}\nu$ mediated by Z' boson @ tree level.
  Competes with SM tree level process mediated by W



- Z couplings : $g^{\mu,\tau}_{Z,L/R}$
  Z' loop induces **modifications of $\boldsymbol{Z}$** couplings



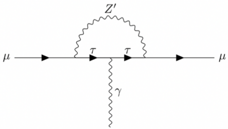
Constraints on $e\tau$ couplings



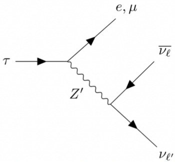
$\Longrightarrow$ Opposite sign **RH** and **LH** ***$e\tau$*** **couplings can account** for the negative deviation of $(g-2)_e$ and τ decays !

Can we have $(g-2)_\mu$ for $\boldsymbol{\mu\tau Z'}$ while complying with τ decay ?

- $(g-2)_\mu$ induced by $\boldsymbol{\tau}$ in the loop

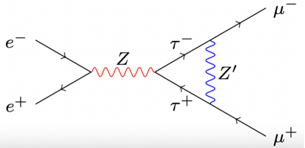


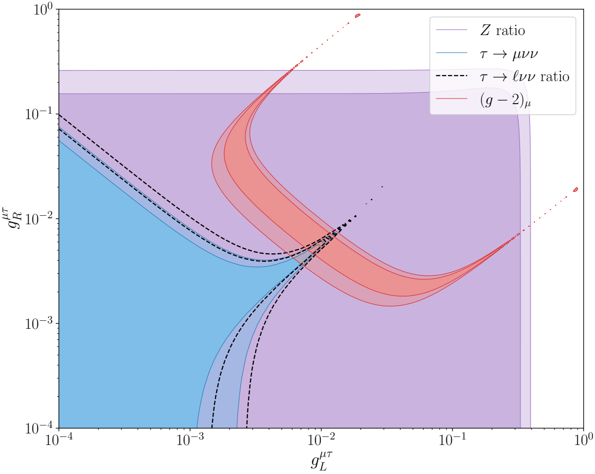
- **$\boldsymbol{\tau}$ decay** : $\tau \to \mu\bar{\nu}\nu$



- **$\boldsymbol{\tau}$ decay universality ratio** : $\dfrac{\tau \to \mu\bar{\nu}\nu}{\tau \to e\bar{\nu}\nu}$

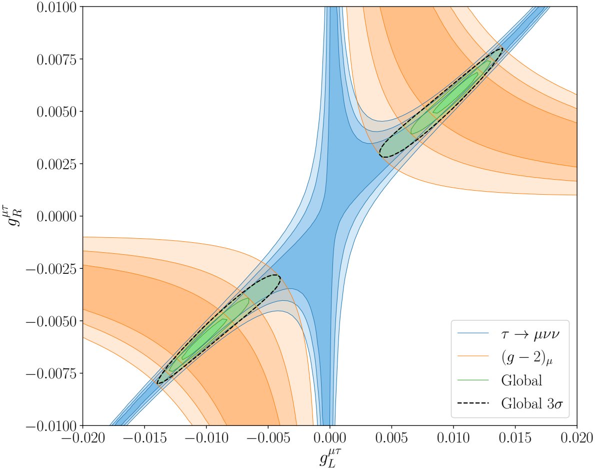
- **$\boldsymbol{Z}$ couplings** : $g^{\mu,\tau}_{Z,L/R}$





Stringent constraints from $(g-2)_\mu$ and τ decays

$\Longrightarrow$ small allowed parameter space



$\Longrightarrow$ Same sign **RH** and **LH** $\boldsymbol{\mu\tau}$ **couplings can account** for the positive deviation of $(g-2)_\mu$ and τ decays !

Conclusion

- Adding **only one** field $\rightarrow$ **light gauge boson Z'** can solve $(g-2)_\mu$ with sizeable $g^{\mu\tau}$, while **satisfying several constraints from flavor observables**
- Stringently constrained parameter space $\Longrightarrow$ **very predictive** model
- $e\mu$ couplings constrained via $\mathrm{Mu} - \overline{\mathrm{Mu}}$ oscillations: cannot account for $(g-2)_e$ $\rightarrow$ need $e\tau$ couplings

$\Rightarrow$ Leads to extremely large $\mu \rightarrow e\gamma$ rate

- Model needs a **scalar for symmetry breaking**: considering scalar contributions to observables

$\Rightarrow$ Could it solve $(g-2)_e$ without large $\mu \rightarrow e\gamma$?

- Can also **extend** the model with additional BSM fermions