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Confronting spin-3/2 and other new fermions with the g-2

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1. The new $(g-2)_\mu$ measurement and its implications

The Fermilab Muon g–2 collaboration has (at last!) released the new measurement of the anomalous magnetic moment of the muon, $a_\mu = \frac{1}{2}(g-2)_\mu$

$$a_\mu^{FL} = (116592040 \pm 54) \times 10^{-11},$$

to be compared with the worldwide consensus in the Standard Model (SM)

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

which implies a 4.2σ deviation from the SM prediction/consensus.

Plan A: new physics at last! We are back to business and those who were hopeless and even disappeared will resurrect ($\approx$ 50 papers on day 1).

Plan B: let us not get too excited! The theory uncertainty is too "uncertain" and the SM part needs to be checked (see BMW lattice paper).

Plan C: well, it is a mix of the two! Part of the deviation is due to bigger theory errors but (a significant) part of it is indeed due to new physics.

Let us buy this option for now (waiting for more TH/EXP clarifications).

In fact, best option: the NP that it implies not too constrained by LHC.

2. Some remarks on spin-3/2 particles

Here, we discuss the impact of the new g–2 value on spin-3/2 particles.

Question: why such a weird thing such as a (high) spin-3/2 particle?

Simple answer is: Why not?

- **Spin-3/2 states exist albeit not elementary, Δ resonance, etc...**
- **They appear in the most celebrated TH construction: supergravity.**
- **They appear in (composite) models of fermionic substructure.**
- **Agnosticism: any BSM is good provided that it is not excluded.**

Corollary to the experimentalist's motto: look at all possible topologies!

Spin-3/2 fields are very complicated and have severe problems due to non-physical degrees of freedom (usually Rarita-Schwinger representation).

List of pathologies: causality violation (superluminal), perturbative unitarity violation, lack of quantization, problem of renormalizability, etc...

In arXiv:2010.02224 and arXiv:2102.13652 JC Criado et al. introduced an EFT for a generic massive higher-spin particle (following Weinberg):

– **contains only physical higher-spin degrees of freedom,**

– **allows for a consistent calculation of physical observables.**

The phenomenology of a charge and colour neutral SM singlet spin-3/2 field $\psi_{3/2}$ has been studied without (for collider searches) and with (for astroparticle and dark matter) a $\mathcal{Z}_2$ symmetry that makes it stable or not.

In general, there are 6 independent linear dimension-7 operators that allow to describe the interactions of the $\psi_{3/2}$ state with the SM fields.

Here, we concentrate on $(g-2)_\mu$ and the relevant effective Hamiltonian is (we have kept only the $\psi_{3/2}$ couplings to the second generation leptons)

$$-\mathcal{H}_{\rm linear} = \frac{1}{\Lambda^3}\psi^{abc}_{3/2}\Big[c_\mu(L^{2T}_{La}\epsilon L^2_{Lb})\mu^*_{Rc} + c_\phi\sigma^{\mu\nu}_{ab}(D_\mu\tilde{\phi})^\dagger D_\nu L^2_{Lc} + c_B\tilde{\phi}^\dagger\sigma^{\mu\nu}_{ab}B_{\mu\nu}L^2_{Lc} + c_W\tilde{\phi}^\dagger\sigma^{\mu\nu}_{ab}\sigma_n W^n_{\mu\nu}L^2_{Lc}\Big] + \text{h.c.},$$

where we neglected all, including fermion mixing; a,b,c are spinor indices; $L^i_{La} = (\nu^i_{ea}, e^i_{La})$, $\phi = (0, H+v)/\sqrt{2}$, B_μ, W_μ are the $U(1)_Y, SU(2)_L$ fields.

– Λ is the NP effective scale, $\Lambda \gtrsim m_{3/2}$ and of order a few (100 GeV).

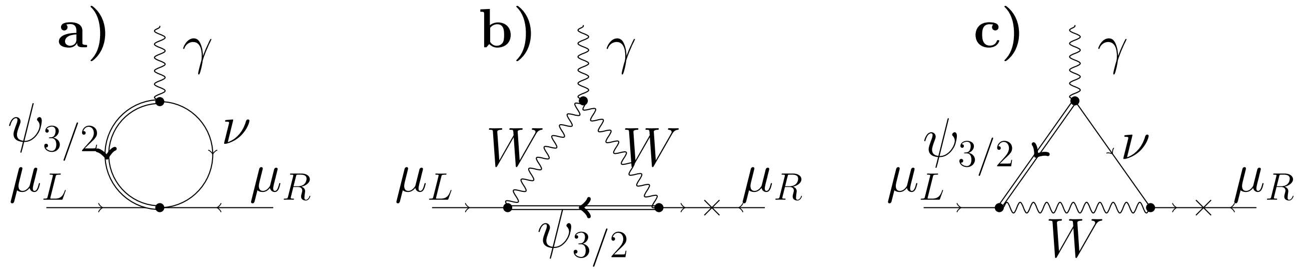
– c_W, c_B, c_μ are of order 1, but c_ϕ taken to be zero (not contributing).

Leading order EFT contribution to g-2 and EDM generated by operators

$$\mathcal{L}_{g-2,\rm EDM} = -\frac{e}{4m_\mu}a_\mu\,\bar{\mu}\sigma_{\mu\nu}\mu\,F^{\mu\nu} - \frac{i}{2}d_\mu\,\bar{\mu}\sigma_{\mu\nu}\gamma_5\mu\,F^{\mu\nu},$$

3. The spin-3/2 contributions to the $(g-2)_\mu$

Generic Feynman diagrams contributing to $g-2$ and the EDM of the muon; the crosses denote the (needed) chirality flip in the external leg, $\mu_L \to \mu_R$.



– **contribution from diagram (a) is $\propto q_\gamma^2$ and zero for on-shell photons;**

– **only (b,c) contribute and they give noting $c_\gamma \equiv -c_B \cos\theta_W + c_W \sin\theta_W$**

$$a_\mu^\psi = \frac{m_\mu^2 v^2 m_{3/2}^2}{8\pi^2 \Lambda^6} \left[|c_W|^2 f_1(m_{3/2}) + \mathrm{Re}(c_W^* c_\gamma)/\sin\theta_W \times f_2(m_{3/2}) \right],$$

divergent loops treated with dimensional regularization in the $\overline{\mathrm{MS}}$ scheme.

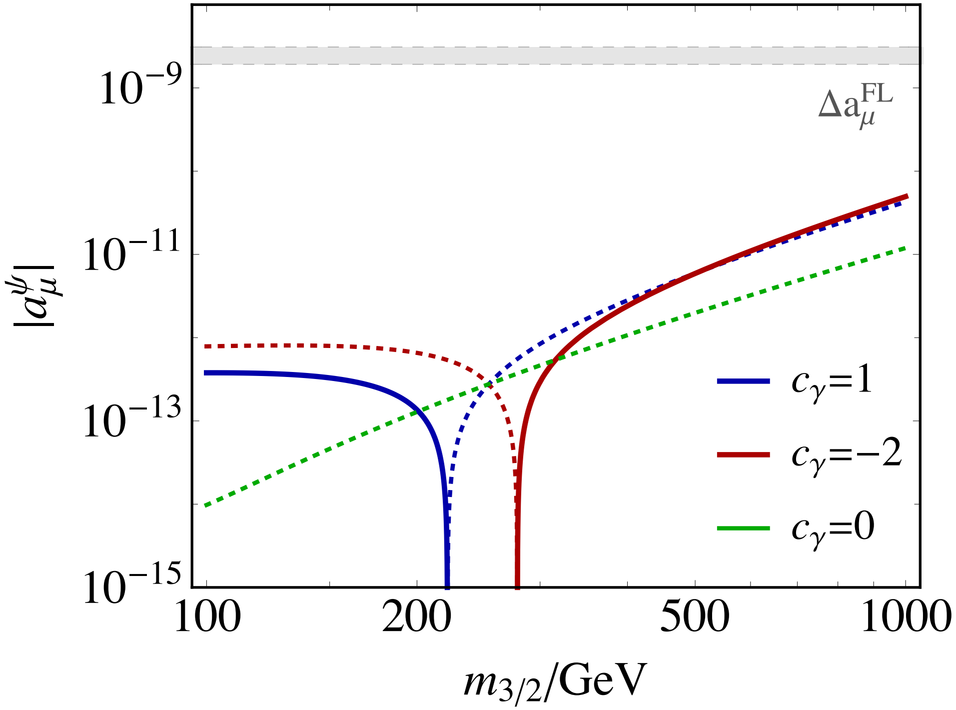
The complicated functions f_1, f_2 simplify for $\Lambda \gtrsim m_{3/2} \gg m_W$,

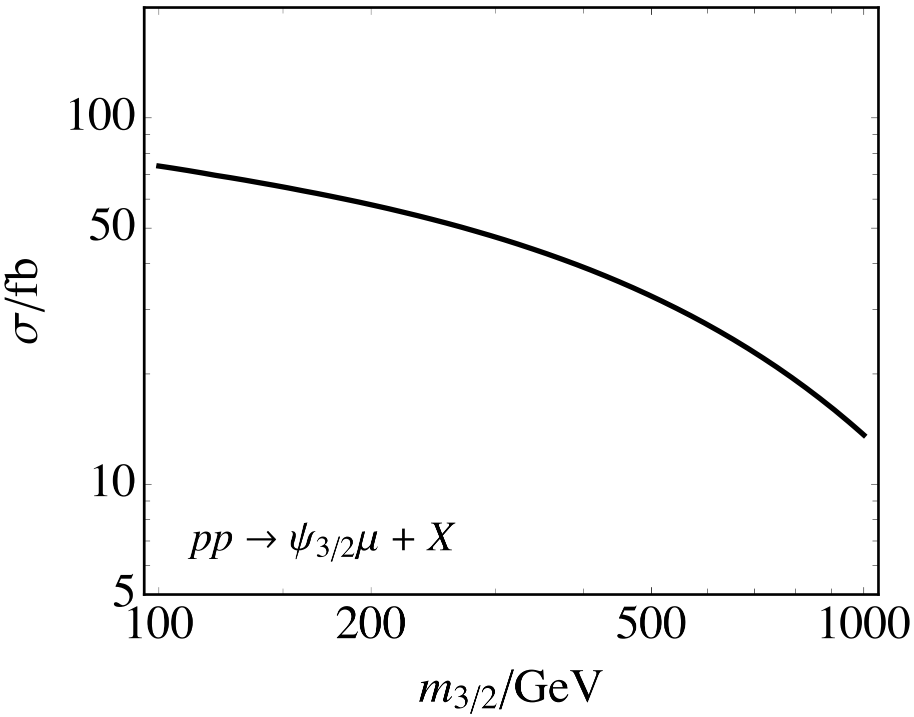
$$f_1(m) = -\frac{13}{27} + \frac{7}{18} \log\left(\frac{\mu^2}{m^2}\right), \qquad f_2(m) = \frac{2}{3} \log\left(\frac{\mu^2}{m^2}\right),$$

where μ is the renormalization scale, taken here to be $\mu = v = 250$ GeV.

The resulting contributions can be roughly summarized by the expression:

$$|\mathbf{a}_\mu^\psi| \lesssim \mathbf{2} \times \mathbf{10}^{-11} \left[\boldsymbol{\Lambda}/\mathbf{TeV}\right]^{-6} \left[\mathbf{m_{3/2}}/\mathbf{TeV}\right]^{2},$$





$\mathbf{a}_\mu^\psi$ **and** $\sigma(\mathbf{q\bar{q}} \to \psi_{\mathbf{3/2}}\mu)$ **at the LHC for** $\boldsymbol{\Lambda} = \mathbf{4}\mu = \mathbf{1}$ **TeV and** $\mathbf{c_W} = \mathbf{1}, \mathbf{c}_\phi = \mathbf{0}$.

For $\boldsymbol{\Lambda} = \mathbf{1}$ **TeV:** $\mathbf{a}_\mu^\psi$ **too small but prospects for** $\psi_{\mathbf{3/2}}$ **at HL-LHC promising.**

For $\boldsymbol{\Lambda} = \mathbf{250}$ **GeV:** $\mathbf{a}_\mu^\psi$ **OK, but excluded (?) at LHC and EFT borderline.**

In fact, situation ≈ similar to what happens for other (spin-1/2) fermions.

4. Comparison with new spin-1/2 fermions

Vector-like leptons: appear in many BSMs; here addressing f hierarchy:

$$\mathcal{L} \propto \mathbf{M_E \bar{E}_L E_R + M_L \bar{L}_R L_L + \bar{\lambda}_{LE} \bar{L}_R E_L \Phi^\dagger + \lambda_{LE} c_{\theta_L} c_{\theta_R} \bar{L}_L E_R \Phi} + \cdots$$

with contributions to $\mathbf{a}_\mu$ for $\lambda_{\mathbf{LE}} = \bar{\lambda}_{\mathbf{LE}} = 1$ keeping only terms $\mathbf{O}(\mathbf{v^2/M^2_{L,E}})$

$$\mathbf{\Delta a}_\mu \simeq \frac{1}{16\pi^2} \frac{\mathbf{m}_\mu^2}{\mathbf{M_L M_E}} \mathrm{Re}(\lambda_{\mathbf{LE}} \bar{\lambda}_{\mathbf{LE}}) \approx \mathbf{10^{-9}}\ (\mathbf{300\ GeV}/\sqrt{\mathbf{M_L M_E}})^2.$$

Excited leptons: appear in all models with fermionic substructure;

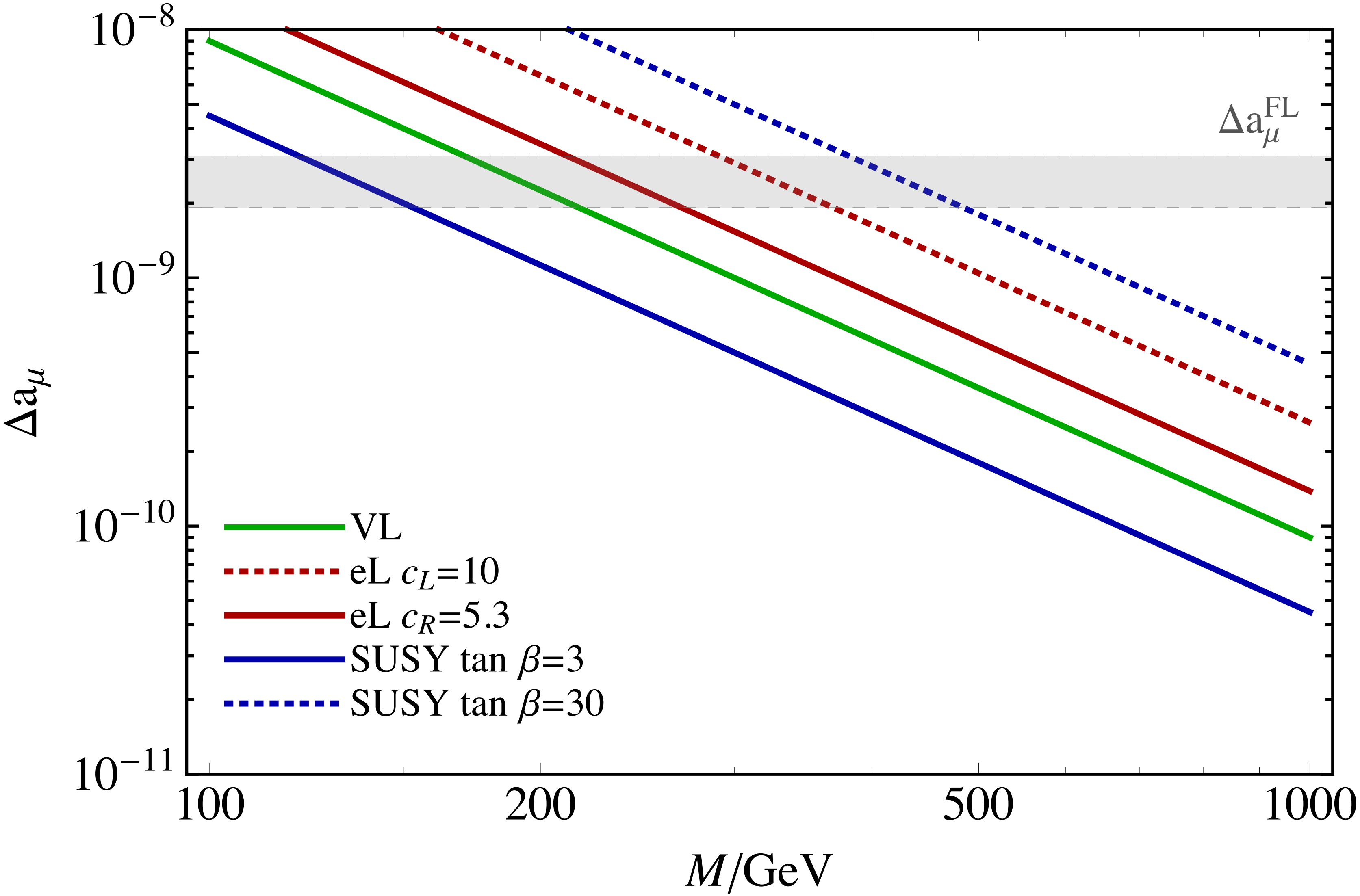
$$\mathcal{L}_{\ell\ell^\star\gamma} = \frac{\mathbf{e}\kappa_{\mathbf{L/R}}}{\sqrt{\mathbf{2}}\mathbf{\Lambda}} \bar{\ell}^\star \sigma^{\mu\nu} \ell_{\mathbf{L/R}} \mathbf{F}_{\mu\nu} + \mathbf{h.c.} \Rightarrow \mathbf{SU(2)_L \times U_Y(1)}$$

with $\kappa_{\mathbf{L/R}} = \mathbf{1, 0}$; contribution to g-2 assuming above and $\mathbf{m}_{\ell^\star} = \mathbf{m}_{\nu_\ell^\star} = \mathbf{\Lambda} \gg \mathbf{m_W}$

$$\mathbf{\Delta a}_\mu = \frac{\alpha}{\pi} \frac{\kappa^2_{\mathbf{L,R}}}{\mathbf{\Lambda^2}} \mathbf{m}_\mu^2 \mathbf{c_{L/R}}, \quad \mathbf{c_L} \simeq \mathbf{10}\ ,\ \mathbf{c_R} \simeq \mathbf{5}$$

Supersymmetric particles: thoroughly discussed; use approximate formula:

$$\mathbf{\Delta a}_\mu \simeq \frac{\alpha}{8\pi \mathbf{s^2_W}} \mathbf{tan}\beta \times \frac{\mathbf{m}_\mu^2}{\tilde{\mathbf{m}}^2} \approx \mathbf{1.5 \times 10^{-11}} \tan\beta \left[\frac{\widetilde{\mathbf{m}}}{\mathrm{TeV}}\right]^{-2},\ \ \tilde{\mathbf{m}} = \mathbf{max}(\mathbf{m}_{\widetilde{\nu}}, \mathbf{m}_{\chi_1^+})$$



Conclusion:

If the discrepancy between theory and experiment in the new $(g-2)_\mu$ measurement is (even only partly) correct, then we are in real business!