New Physics Models for $(g-2)_\mu$

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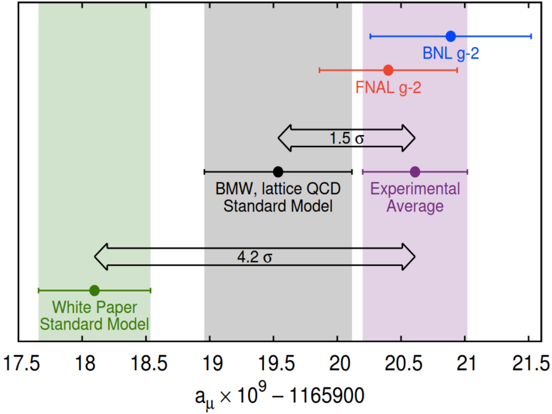
The Anomalous Anomalous Magnetic Moment



4.2 σ discrepancy between the experimental average and the SM consensus.

For this talk we will assume this is due to new physics

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

$(g-2)_\mu$ and the Scale of New Physics (1)

- The leading new physics operator that modifies the anomalous magnetic moment of the muon and that respects $SU(2)_L \times U(1)_Y$

$$\mathcal{H}_{\text{eff}} = -\frac{C}{\Lambda_{\text{NP}}^2} H(\bar{\mu}\sigma_{\alpha\beta}\mu)F^{\alpha\beta}$$

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$$\mathcal{H}_{\text{eff}} = -\frac{C}{\Lambda_{\text{NP}}^2} H(\bar{\mu}\sigma_{\alpha\beta}\mu)F^{\alpha\beta}$$

- After electroweak symmetry breaking, this gives

$$\Delta a_\mu \sim C\frac{m_\mu v}{\Lambda_{\text{NP}}^2} \simeq 250 \times 10^{-11} \times C \times \left(\frac{100\text{ TeV}}{\Lambda_{\text{NP}}}\right)^2$$

- In principle, one can probe extremely high scales with $(g-2)_\mu$.

$(g-2)_\mu$ and the Scale of New Physics (2)

- In practice, the Wilson coefficient C is typically tiny
- Loop suppression, and suppression by the muon Yukawa (assuming the absence of new sources of LFU violation)

$$C \sim \frac{1}{16\pi^2} Y_\mu \sim \frac{1}{16\pi^2} \frac{m_\mu}{v} \sim 3 \times 10^{-6}$$

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- This gives a much smaller estimate

$$\Delta a_\mu \sim \frac{1}{16\pi^2} \frac{m_\mu^2}{\Lambda_{\rm NP}^2} \simeq 250 \times 10^{-11} \times \left(\frac{170\ \text{GeV}}{\Lambda_{\rm NP}} \right)^2$$

- Many explanations of $(g-2)_\mu$ predict new physics not far above the electroweak scale (or even considerably below)

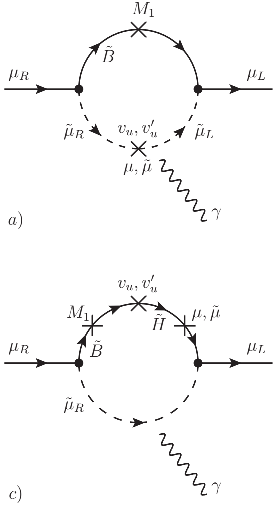
New Physics Models

I will discuss the following scenarios

- Heavy New Physics
  - SUSY (MSSM and MSSM with extended Higgs sector)
  - Leptoquarks (very briefly)
- Light New Physics
  - dark photon (very briefly)
  - $L_\mu - L_\tau$ gauge boson
  - axion like particles (very briefly)

SUSY

$(g-2)_\mu$ in the MSSM (1)



$(g-2)_\mu$ in the MSSM (2)

- Approximation of the loops containing Binos
  (in the limit of universal SUSY masses and $m^2_{\text{SUSY}} \gg m^2_Z$)

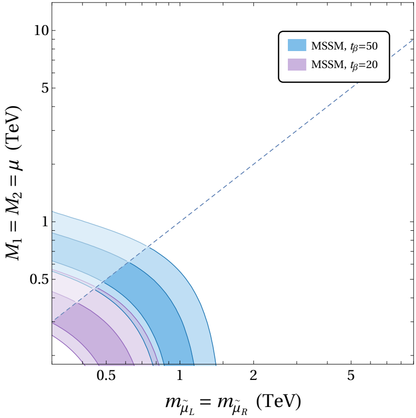
$$\Delta a_\mu^{\tilde{b}} \sim \frac{g'^2}{16\pi^2} \frac{m_\mu^2}{m_{\tilde{\mu}}^2} \frac{\mu M_1}{m_{\tilde{\mu}}^2} \frac{1}{12} \frac{\tan\beta}{1+\epsilon_\ell \tan\beta}$$

- Approximation of the loops containing Winos
  (in the limit of universal SUSY masses and $m^2_{\text{SUSY}} \gg m^2_Z$)

$$\Delta a_\mu^{\tilde{w}} \sim \frac{g^2}{16\pi^2} \frac{m_\mu^2}{m_{\tilde{\mu}}^2} \frac{\mu M_2}{m_{\tilde{\mu}}^2} \frac{5}{12} \frac{\tan\beta}{1+\epsilon_\ell \tan\beta}$$

- Suppression by loop factor and smallish loop functions
- Muon Yukawa coupling is enhanced by $\tan\beta$

WA, Gadam, Gori, Hamer 2104.08293

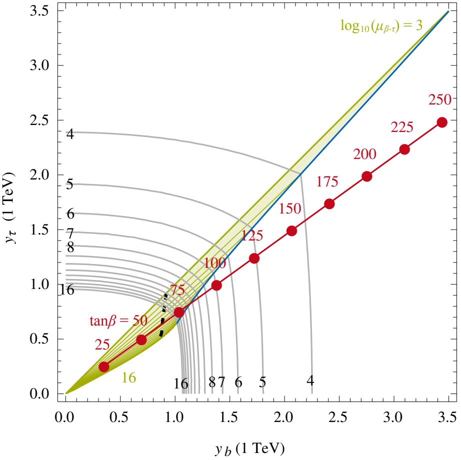


- (at least some) SUSY particles need to be below 1 TeV to explain the $(g-2)_\mu$ discrepancy
- good news for colliders...
- ...but why haven't we seen those particles at the LHC?

$$\Delta a_\mu \simeq 260 \times 10^{-11} \times \left(\frac{\tan\beta}{50}\right)^2 \left(\frac{500\text{ GeV}}{m_\text{SUSY}}\right)^2$$

Very Large $\tan\beta$?

WA, Straub 1004.1993



- For too large $\tan\beta$, the bottom and tau Yukawa couplings develop Landau poles
- typical limit in the MSSM

$$\tan\beta \lesssim 70$$

- corresponds to a small muon Yukawa

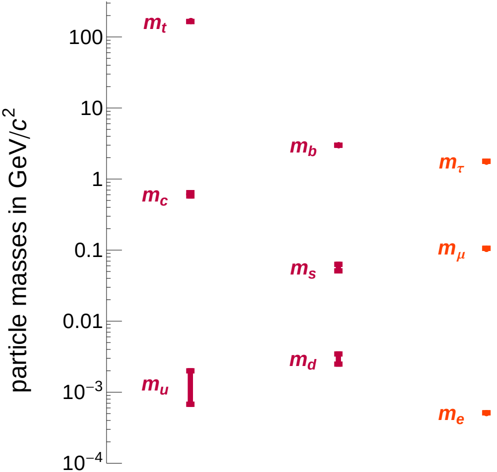
$$Y_\mu \simeq \sqrt{2}\frac{m_\mu}{v}\tan\beta$$

$$\lesssim 4 \times 10^{-2}$$

Basic idea to get a larger Δa_μ:

increase the muon Yukawa coupling
beyond what is possible in the MSSM
(requires a new source of LFUV)

Quark and Lepton Masses



What is the origin of the hierarchies in the fermion spectrum?

Maybe the first and second generation fermions are light because their mass is coming from a subdominant source of electroweak symmetry breaking?

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

Ghosh, Gupta, Perez 1508.01501

Botella, et al. 1602.08011

Das, Kao hep-ph/9511329

Blechmann, et al. 1009.1612

A 2HDM with Non-Standard Flavor Structure

- 2 Higgs doublets H and H' with vevs v and v' and Yukawas Y and Y'

$$\mathcal{L} = (Y_u \hat{H}^c + Y'_u H'^{\,c})\bar{q}u + (Y_d H + Y'_d H')\bar{q}d + (Y_\ell H + Y'_\ell H')\bar{\ell}e$$

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- Fermions receive mass from both Higgs bosons

$$\mathcal{M}_u = vY_u + v' Y'_u \,, \quad \mathcal{M}_d = vY_d + v' Y'_d \,, \quad \mathcal{M}_\ell = vY_\ell + v' Y'_\ell$$

- Invoke some mechanism such that Yukawa couplings Y are rank 1, while the Yukawa couplings Y' are generic (apart from 1st/2nd generation hierarchy)

$$\mathcal{M}_0 \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix} , \quad \Delta\mathcal{M} \simeq \begin{pmatrix} m_e & O(m_e) & O(m_e) \\ O(m_e) & m_\mu & O(m_\mu) \\ O(m_e) & O(m_\mu) & O(m_\mu) \end{pmatrix}$$

(similar in the quark sector)

Flavor Changing Neutral Currents

- 3rd generation obtains mass from the first doublet H,
  1st and 2nd generation obtains mass from the second doublet H'
- If the vev of H' is very small, one can have $\mathcal{O}(1)$ Yukawa couplings of 2nd generation fermions

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(because Y and Y' cannot be diagonalized simultaneously)

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- However, there are residual flavor symmetries that suppress FCNCs

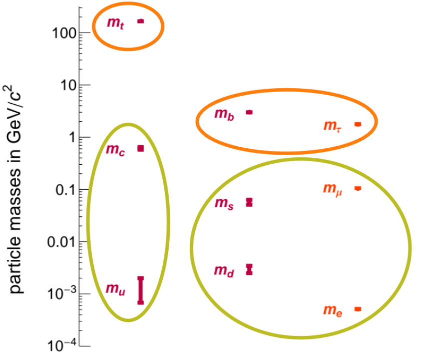
$$\mathcal{M}_0^u \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_t \end{pmatrix} ~,~~ \mathcal{M}_0^d \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_b \end{pmatrix} ~,~~ \mathcal{M}_0^\ell \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

- The rank 1 Yukawa couplings preserve a $SU(2)^5$ flavor symmetry for the light two generations of quarks and leptons

A SUSY Version of the "Flavorful" Higgs Sector

- Anomaly cancellation $\to$ need four Higgs doublets H_u, H'_u, H_d, H'_d
- The superpotential of the model is

$$W = \mu_1 \hat{H}_u \hat{H}_d + \mu_2 \hat{H}'_u \hat{H}'_d + \mu_3 \hat{H}'_u \hat{H}_d + \mu_4 \hat{H}_u \hat{H}'_d$$
$$(Y_u \hat{H}_u + Y'_u \hat{H}'_u)\hat{Q}\hat{U}^c + (Y_d \hat{H}_d + Y'_d \hat{H}'_d)\hat{Q}\hat{D}^c + (Y_\ell \hat{H}_d + Y'_\ell \hat{H}'_d)\hat{L}\hat{E}^c$$



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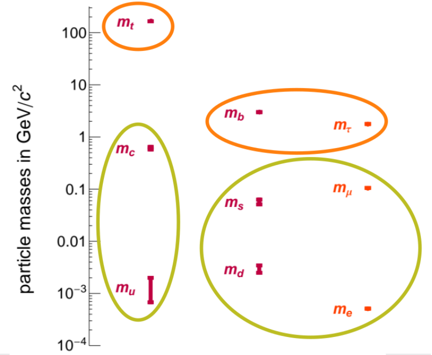

- Four μ terms
- Third generation gets mass from H_u, H_d
- First and second generation get mass from H'_u, H'_d
- Focus on the lepton sector in the following

Muon and Smuon Masses

4 Higgs doublets $\Rightarrow$ 4 vevs v_u, v_u', v_d, v_d', with $v_u^2 + {v_u'}^2 + v_d^2 + {v_d'}^2 = v^2$

- Useful to introduce the ratios

$$\tan\beta = \frac{v_u}{v_d} ~, \quad \tan\beta_u = \frac{v_u}{v_u'} ~, \quad \tan\beta_d = \frac{v_d}{v_d'}$$

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- $\tan\beta_d$ controls the size of muon Yukawa
(independently of the tau and bottom Yukawas)

$$Y'_{\mu\mu} \simeq \sqrt{2}\frac{m_\mu}{v}\frac{\tan\beta\tan\beta_d}{1+\epsilon_\ell\tan\beta\tan\beta_d} \ , \qquad Y_\tau \simeq \sqrt{2}\frac{m_\tau}{v}\frac{\tan\beta}{1+\epsilon_\tau\tan\beta}$$

- Muon Yukawa $Y'_{\mu\mu}$ can be $\mathcal{O}(1)$ without running into Landau poles

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- Muon Yukawa $Y'_{\mu\mu}$ can be $\mathcal{O}(1)$ without running into Landau poles

- $\tan\beta_d$ also boosts left-right mixing of smuons

$$M_{\tilde\mu}^2 \simeq \begin{pmatrix} m^2_{\tilde\mu_L} & -m_\mu\mu_4\frac{\tan\beta\tan\beta_d}{1+\epsilon_\ell\tan\beta\tan\beta_d} \\ -m_\mu\mu_4\frac{\tan\beta\tan\beta_d}{1+\epsilon_\ell\tan\beta\tan\beta_d} & m^2_{\tilde\mu_R} \end{pmatrix}$$

Chargino and Neutralino Spectrum

- 4 Higgsinos + Winos + Bino ⇒ 3 charginos + 6 neutralinos
- Chargino mass matrix

$$M_{\chi^\pm} = \begin{pmatrix} M_2 & \frac{g}{\sqrt{2}} v_u & \frac{g}{\sqrt{2}} v_u' \\ \frac{g}{\sqrt{2}} v_d & \mu_1 & \mu_3 \\ \frac{g}{\sqrt{2}} v_d' & \mu_4 & \mu_2 \end{pmatrix}$$

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- It is convenient to first diagonalize the Higgsino block

$$\begin{pmatrix} \cos\theta_d & \sin\theta_d \\ -\sin\theta_d & \cos\theta_d \end{pmatrix} \begin{pmatrix} \mu_1 & \mu_3 \\ \mu_4 & \mu_2 \end{pmatrix} \begin{pmatrix} \cos\theta_u & \sin\theta_u \\ -\sin\theta_u & \cos\theta_u \end{pmatrix} = \begin{pmatrix} \mu & 0 \\ 0 & \tilde{\mu} \end{pmatrix}$$

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  Generically expect the rotation angles θ_u and θ_d to be $\mathcal{O}(1)$

- Remaining off-diagonal entries are of the order of the electroweak scale and can be treated perturbatively
- Analogous treatment for the neutralinos
- The $\tilde{H}'_d$ component of the charginos and neutralinos can have $\mathcal{O}(1)$ coupling to muons

$(g-2)_\mu$ in the FSSM

- Bino and Wino contributions have a structure that is analogous to the MSSM

$$\Delta a_\mu^{\tilde{b}} \sim \frac{g'^2}{16\pi^2} \frac{m_\mu^2}{m_{\tilde{\mu}}^2} \frac{M_1}{m_{\tilde{\mu}}^2} \left(\mu \sin\theta_d \cos\theta_u + \tilde{\mu} \cos\theta_d \sin\theta_u\right) \frac{1}{12} \frac{\tan\beta \tan\beta_d}{1+\epsilon_\ell \tan\beta \tan\beta_d}$$

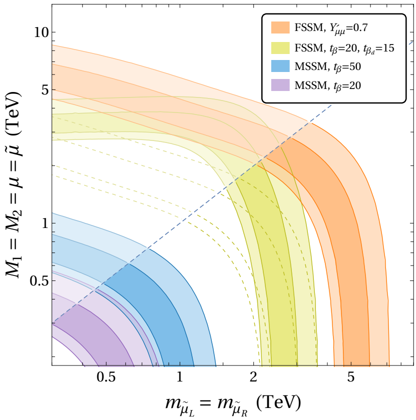
$$\Delta a_\mu^{\tilde{w}} \sim \frac{g^2}{16\pi^2} \frac{m_\mu^2}{m_{\tilde{\mu}}^2} \frac{M_2}{m_{\tilde{\mu}}^2} \left(\mu \sin\theta_d \cos\theta_u + \tilde{\mu} \cos\theta_d \sin\theta_u\right) \frac{5}{12} \frac{\tan\beta \tan\beta_d}{1+\epsilon_\ell \tan\beta \tan\beta_d}$$

- Contributions from the Higgsinos with mass μ and the Higgsinos with mass $\tilde{\mu}$

- Main qualitative difference to the MSSM: additional enhancement by $\tan\beta_d$

$^{(*)}$ Flavorful Supersymmetric Standard Model

WA, Gadam, Gori, Hamer 2104.08293



- Plot assumes $\mathcal{O}(1)$ Higgsino mixing: $\theta_u = \theta_d = \pi/2$
- SUSY particles can be several TeV and can still explain the $(g-2)_\mu$ discrepancy

$$\Delta a_\mu \simeq 240 \times 10^{-11} \times \left(\frac{Y'_{\mu\mu}}{0.7}\right)^2 \left(\frac{2.5\text{ TeV}}{m_{\text{SUSY}}}\right)^2$$

Anomalous Magnetic Moments of Electron and Tau

- The minimally broken $SU(2)^2$ lepton flavor symmetry predicts

$$\Delta a_e \simeq \frac{m_e^2}{m_\mu^2} \Delta a_\mu \simeq 5.8 \times 10^{-14} \times \left(\frac{\Delta a_\mu}{251 \times 10^{-11}} \right)$$

$\rightarrow$ well within current uncertainties

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- No precise prediction for the tau, but generic expectation

$$\Delta a_\tau \sim \frac{m_\tau^2}{m_\mu^2}\frac{1}{\tan\beta_d}\Delta a_\mu \simeq 4.7 \times 10^{-8} \times \left(\frac{15}{\tan\beta_d}\right) \times \left(\frac{\Delta a_\mu}{251 \times 10^{-11}}\right)$$

$\to$ far below foreseeable experimental sensitivities

Lepton Flavor Violating Tau Decays

- Lepton flavor violation depends on unknown coefficients in the Yukawa couplings $Y'_{\ell\ell'}$. But can get order of magnitude expectations:

$$\mathrm{BR}(\tau \to \mu\gamma) \simeq 24\pi^3 \alpha_{\mathrm{em}} \frac{v^4}{m_\mu^4} (\Delta a_\mu)^2 \left(x_{\tau\mu}^2 + x_{\mu\tau}^2\right) \times \mathrm{BR}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)$$

$$\simeq 1.7 \times 10^{-8} \times \left(\frac{\Delta a_\mu}{251 \times 10^{-11}}\right)^2 \left[\left(\frac{x_{\tau\mu}}{0.01}\right)^2 + \left(\frac{x_{\mu\tau}}{0.01}\right)^2\right]$$

$$\mathrm{BR}(\tau \to e\gamma) \simeq 24\pi^3 \alpha_{\mathrm{em}} \frac{v^4}{m_\mu^4} \frac{m_e^2}{m_\mu^2} (\Delta a_\mu)^2 \left(x_{\tau e}^2 + x_{\mu e}^2\right) \times \mathrm{BR}(\tau \to e\nu_\tau\bar{\nu}_\mu)$$

$$\simeq 4.1 \times 10^{-9} \times \left(\frac{\Delta a_\mu}{251 \times 10^{-11}}\right)^2 \left[\left(\frac{x_{\tau e}}{1.0}\right)^2 + \left(\frac{x_{e\tau}}{1.0}\right)^2\right]$$

- $\mathrm{BR}(\tau \to \mu\gamma)$ already constrained by BaBar and Belle
- $\mathrm{BR}(\tau \to e\gamma)$ in reach of Belle II

Lepton Flavor Violating Muon Decay

- Lepton flavor violating $\mu \to e$ transitions are suppressed by the approximate $SU(2)^2$ lepton flavor symmetry

- Look, e.g., at the decay $\mu \to e\gamma$

$$\text{BR}(\mu \to e\gamma) \simeq 24\pi^3 \alpha_\text{em} \frac{v^4}{m_\mu^4} \frac{m_e^2}{m_\tau^2} (\Delta a_\mu)^2 \left(x_{e\tau}^2 x_{\tau\mu}^2 + x_{\mu\tau}^2 x_{\tau e}^2 \right)$$

$$\simeq 8.2 \times 10^{-15} \times \left(\frac{\Delta a_\mu}{251 \times 10^{-11}} \right)^2 \left[\left(\frac{x_{e\tau} x_{\tau\mu}}{0.01} \right)^2 + \left(\frac{x_{\mu\tau} x_{\tau e}}{0.01} \right)^2 \right]$$

- Almost 2 orders of magnitude below the MEG bound

Leptoquarks

Enhanced Leptoquark Contributions to $g - 2$

- The magnetic dipole moments of leptons transform as a $3_L \times \bar{3}_E$ under the SM flavor symmetry
- In the absence of new sources of symmetry breaking they are proportional to the (small) SM lepton Yukawa

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- Leptoquarks can provide an effective $3_L \times \bar{3}_E$ if they couple to both LR and RH leptons
- Example: the $S_1 = (\mathbf{3}, \mathbf{1}, -1/3)$ leptoquark with couplings

$$\mathcal{L} \supset \bar{q}_L^c \lambda_L \ell_L S_1^* + \bar{u}_R^c \lambda_R e_R S_1^*$$

$$\lambda_L^\dagger \cdot Y_u \cdot \lambda_R \sim (3_L \times 3_Q) \cdot (\bar{3}_Q \times 3_U) \cdot (\bar{3}_U \times \bar{3}_E) \sim 3_L \times \bar{3}_E$$

- Can explain the anomaly with fairly heavy leptoquarks

$$\Delta a_\mu \simeq \frac{\mathrm{Re}(\lambda_L^{\mu t\,*} \lambda_R^{t\mu})}{4\pi^2} \frac{m_\mu m_t}{m_{\mathrm{LQ}}^2} \left[\log\left(\frac{m_{\mathrm{LQ}}^2}{m_t^2} \right) - \frac{7}{4} \right]$$

Dark Photon

Dark Photon Contribution to $g-2$

- introduce a new massive $U(1)$ gauge boson that has a kinetic mixing with the SM photon

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{1}{2} m_X^2 X_\mu X^\mu + \frac{1}{2} \epsilon X_{\mu\nu} F^{\mu\nu}$$

- diagonalizing gives a dark photon with ϵ suppressed couplings to the EM current of the SM

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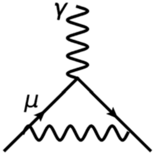
- gives 1-loop corrections to the g-2

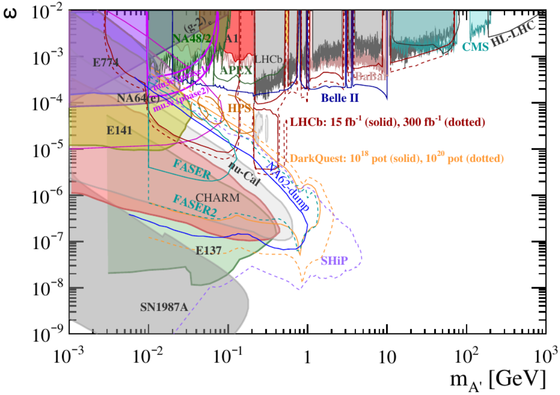
$$\Delta a_\ell \simeq \begin{cases} \epsilon^2 \frac{\alpha}{2\pi} \;, & \text{if } \; m_X \ll m_\ell \\ \epsilon^2 \frac{\alpha}{3\pi}\frac{m_\ell^2}{m_X^2} \;, & \text{if } \; m_X \gg m_\ell \end{cases}$$



Visible Dark Photon Parameter Space

- the minimal scenario has long been ruled out by searches for visibly decaying dark photons
- (the most recent plots don't even show anymore the region of parameter space that is preferred by $(g-2)_\mu$)

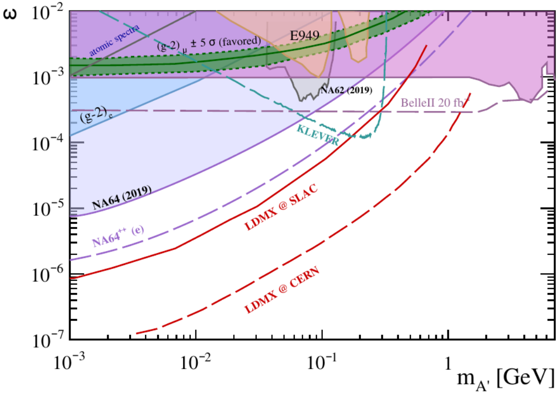
Agrawal et al. 2102.12143



Invisible Dark Photon Parameter Space

- many constraints are absent if one lets the dark photon decay to dark matter with $\simeq$ 100% branching ratio
- dedicated searches for invisible dark photons still exclude all the parameter space in which $(g-2)_\mu$ could be explained

Agrawal et al. 2102.12143



Gauged $L_\mu - L_\tau$

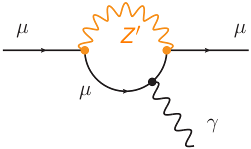
Muon Anomalous Magnetic Moment

New gauge bosons are well known candidates to explain $(g-2)_\mu$

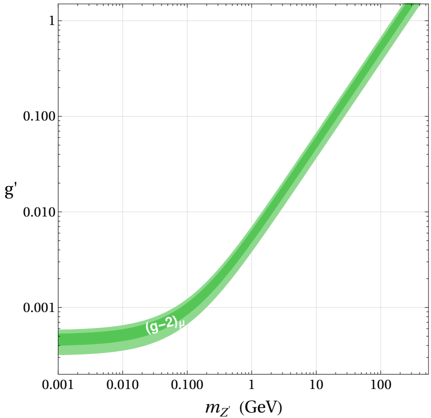
(Greljo, Stangl, Thomsen, Zupan 2203.13731)

in the following I focus on $L_\mu - L_\tau$

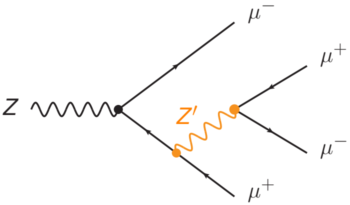
Z' of gauged $L_\mu - L_\tau$ contributes to $(g-2)_\mu$ at the 1-loop level



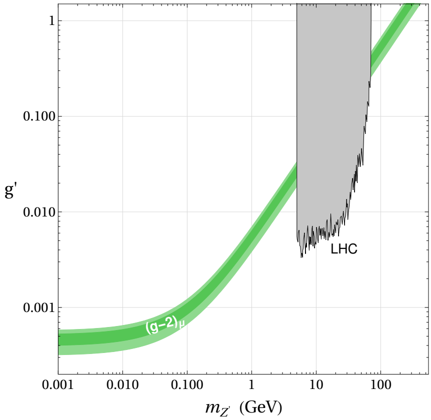
$$\Delta a_\mu \simeq \frac{(g')^2}{12\pi^2}\frac{m_\mu^2}{m_{Z'}^2} + \mathcal{O}\left(\frac{m_\mu^4}{m_{Z'}^4}\right)$$



LHC Searches

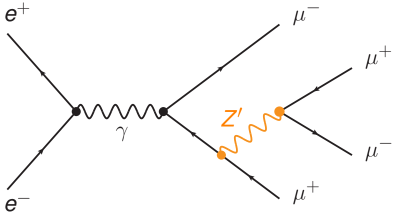


dedicated search for the $L_\mu - L_\tau$ gauge boson (CMS 1808.03684)



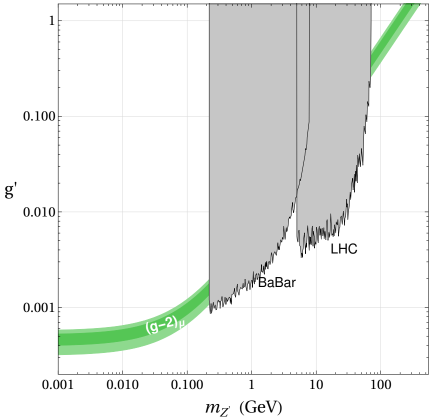
Direct Searches at B-factories

$$e^+e^- \to 2\mu Z' \to 4\mu$$



BaBar 1606.03501

(Can be improved at Belle II)



Direct Searches at B-factories

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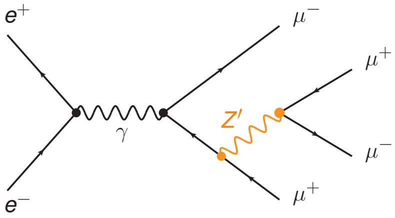
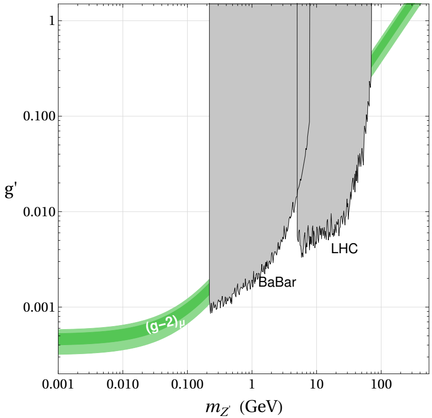


BaBar 1606.03501

(Can be improved at Belle II)



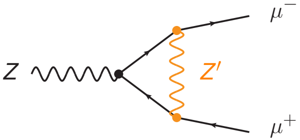
Not yet sensitive to the region below the di-muon threshold

$$e^+e^- \to \mu^+\mu^- + E_{\text{miss}}$$

Belle II 1912.11276

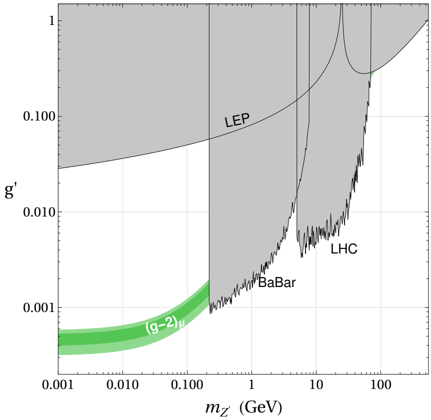
Modified Z Couplings to Leptons

loops involving the Z' lead to corrections of the couplings of the SM Z to muons, taus and neutrinos



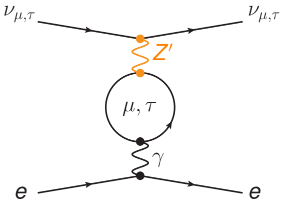
$\rightarrow$ constraints from LEP measurements

WA, Gori, Pospelov, Yavin 1403.1269



Neutrino-Electron Scattering

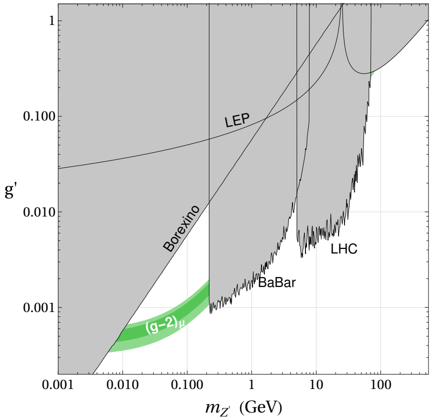
Borexino measures the scattering rate of solar neutrinos on electrons



tiny momentum transfer
$\Rightarrow$ Z' can mix with photon

relevant constraint at low masses

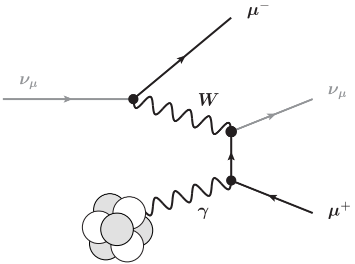
Kamada, Yu 1504.00711



Neutrino Tridents

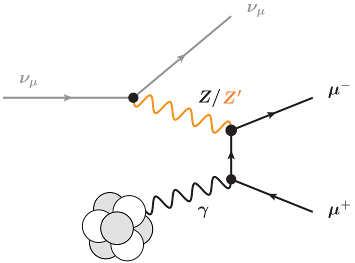
The Z' contributes to trident production

effect has some dependence on the
neutrino beam spectrum



$$\frac{\sigma^{\text{CCFR}}}{\sigma^{\text{CCFR}}_{\text{SM}}} \simeq \frac{1.13 + \left(1 + 4s_W^2 + \frac{2v^2 (g')^2}{M_{Z'}^2}\right)^2}{1.13 + (1 + 4s_W^2)^2}$$

(for Z' masses $\gtrsim$ few GeV)



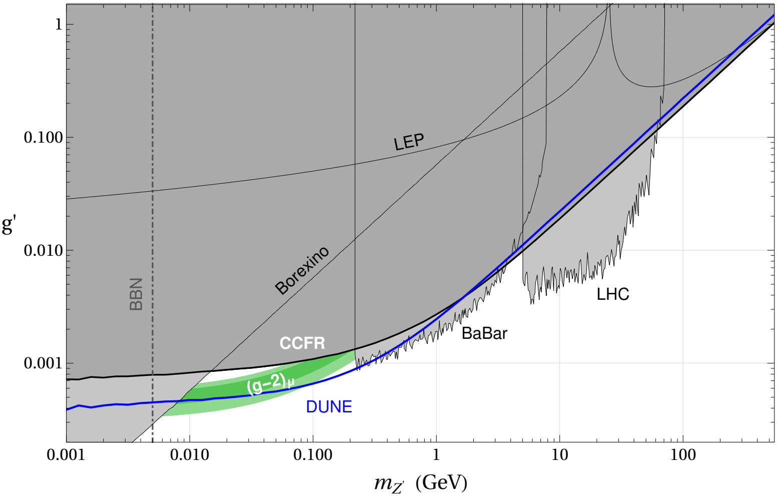
$$\frac{\sigma^{\text{DUNE}}}{\sigma^{\text{DUNE}}_{\text{SM}}} \simeq \frac{1.54 + \left(1 + 4s_W^2 + \frac{2v^2 (g')^2}{M_{Z'}^2}\right)^2}{1.54 + (1 + 4s_W^2)^2}$$

(for Z' masses $\gtrsim$ few hundred MeV)

(WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765)

Summary of Constraints on $L_\mu - L_\tau$

WA, Gori, Pospelov, Yavin, 1406.2332; WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765



Issues with the CCFR Result?

NuTeV analysis identified an additional background that was not included by CCFR

Furthermore, the neutrino trident process must be considered in combination with the expected signal from

diffractive charm production in experiments that are only sensitive to two-muon final states. This point has not been recognized in previous measurements of neutrino tridents.

and improved signal modeling

This procedure incorporated all possible kinematic correlations between the two muons and represents an improvement over previous methods

NuTeV, Phys.Rev.D 61, 092001 (2000)

NuTeV result is somewhat less constraining ($\sim$ factor 2 on the coupling)

Covering the Remaining Parameter Space

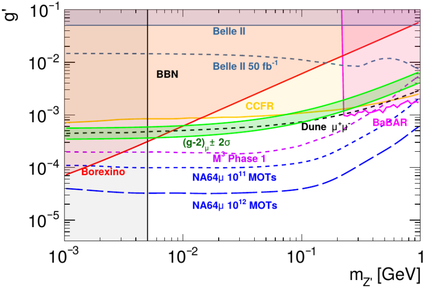
- Neutrino tridents at DUNE (WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765)
- $e^+e^- \to \mu^+\mu^- + Z'(\to$ invisible) at Belle II (Belle II 1912.11276)
- $K \to \mu\nu + Z'(\to$ invisible) at NA62 (Krnjaic et al. 1902.07715)
- $eN \to eN + Z'(\to$ invisible) at NA64 (NA64 2206.03101)
  (relies on kinetic mixing with photon for the production)

Covering the Remaining Parameter Space

- Neutrino tridents at DUNE (WA, Gori, Martin-Albo, Sousa, Wallbank 1902.06765)
- $e^+e^- \to \mu^+\mu^- + Z'(\to$ invisible) at Belle II (Belle II 1912.11276)
- $K \to \mu\nu + Z'(\to$ invisible) at NA62 (Krnjaic et al. 1902.07715)
- $eN \to eN + Z'(\to$ invisible) at NA64 (NA64 2206.03101)
  (relies on kinetic mixing with photon for the production)

- Ultimate test: muon beam dump experiments NA64μ or M^3
  (Sieber et al. 2110.15111; Kahn et al. 1804.03144)

  $\mu N \to \mu N + Z'(\to$ invisible)

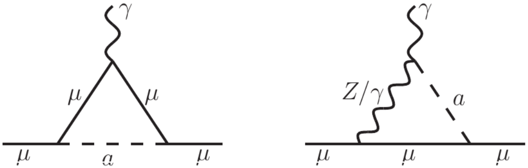


Axion Like Particles

Marciano et al. 1607.01022; Bauer et al. 1708.00443, 1908.00008, 2110.10698; Buen-Abad et al. 2104.03267

consider an ALP coupled to photons and muons

$$\mathcal{L} \supset c_{\mu\mu} \frac{\partial^\alpha a}{2f} (\bar{\mu}\gamma_\alpha\gamma_5\mu) + \frac{\alpha}{4\pi} c_{\gamma\gamma} \frac{a}{f} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

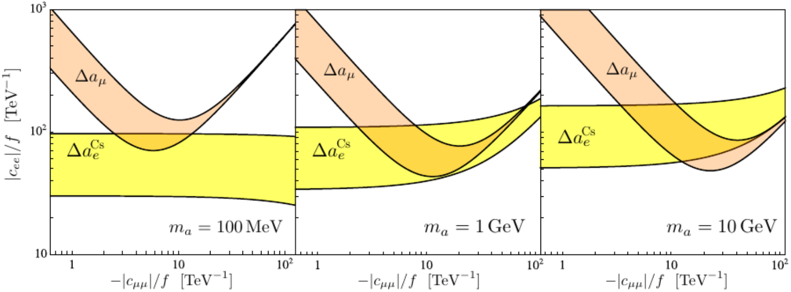


$$\Delta a_\mu \simeq -\frac{m_\mu^2}{16\pi^2 f^2} \left[c_{\mu\mu}^2 + \frac{2\alpha}{\pi} c_{\gamma\gamma}^{\text{eff}} c_{\mu\mu} \log\left(\frac{\Lambda^2}{m_\mu^2}\right) \right] \quad \text{for } m_a \ll m_\mu$$

(can also have lepton flavor violating contributions)

ALP Parameter Space

Bauer et al. 2110.10698



- Need very large couplings
  $\leftrightarrow$ very small axion decay constant $f \lesssim$ 100 GeV
- Hard to imagine a UV completion that is not yet ruled out
- Can try to explain $(g-2)_\mu$ with lepton flavor violating couplings (enhancement by m_τ/m_μ) but strong constraints from LFV processes

Summary

- In the absence of new sources of LFUV, the anomaly in $(g-2)_\mu$ points to new physics not far above the weak scale
- NP scale can be several TeV if there is a new flavor spurion $\sim \bar{3}_L \times 3_E$ with $O(1)$ muon coupling
- Light new physics explanations (far below the weak scale) can be viable and provide targets for direct searches