Dark Sectors and Lepton $g - 2$

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$\vec{\mu} = \frac{g e}{2m} \vec{S}$

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The Big Picture

- The Standard Model (SM) a very successful theory
  - Precise description of a large set of microscopic phenomena

- However, SM *incomplete* based on firm evidence
  - Neutrino masses: $m_\nu \lesssim 0.1$ eV
    - A large collection of neutrino oscillation data
  - Dark matter (DM) (\(~ 27\%\) )
    - So far, gravitational evidence only
    - Stable on cosmological time scales
    - Feeble interactions with ordinary matter
  - \(~ 68\%\) dark energy, maybe vacuum energy, no dynamics
  - “Visible” matter: unknown origin (\(~ 5\%\) )
• Strong case for new physics

• Yet SM appears well-insulated from new phenomena

• To decouple Beyond SM (BSM) physics:

(A) Large masses or (B) Small couplings

• Type (A): new physics above weak scale (mass $\gtrsim 100$ GeV)
  • Perhaps associated with EWSB
  • Hierarchy: Why is $m_H \ll M_P$ (or other large mass scales)?
  • E.g. supersymmetry, compositeness, extra dimensions, . . .
  • Probed at high energy colliders

• Type (B): possible to have low scale new states (mass $\lesssim 1$ GeV)
  • Suppressed couplings: hard to detect, requires large statistics, precision
  • E.g. axions, sterile neutrinos, dark vector bosons, . . .
  • Intensity physics: fixed target, beam dump, $B$-facilities, neutrino oscillations, . . .
Traditionally, BSM has been assumed to be type (A)

- Lack of evidence at LHC so far

Recent years: a surge of interest in BSM of type (B)

- Often phenomenological, motivated by certain anomalies
- Models are typically simple, may not have a connection to type (A)
- Largely independent of hierarchy (naturalness)

One long-standing $\sim 3.7\sigma$ deviation from SM: $g_\mu - 2$

Blum et al. [RBC and UKQCD Collaborations], 2018; Keshavarzi, Nomura, Teubner, 2018

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{th}} = (274 \pm 73) \times 10^{-11}$$

For comparison, the SM EW contribution is $a_\mu^{\text{EW}} = 153.6(1.0) \times 10^{-11}$ (PDG)

- For some type (A) resolutions see D. Stockinger’s talk

- The rest of the talk a survey of some type (B) models
Dark Forces

• Assume a “dark” sector $U(1)_d$

• Minimal extension that captures key physics

• Mediated by vector boson $Z_d$ of mass $m_{Z_d}$ coupling $g_d$

• Interaction with SM: dim-4 operator (portal) via mixing

• $m_{Z_d} \lesssim 1$ GeV has been invoked in various contexts

• DM interpretation of astrophysical data
  

• Explaining the $g_\mu - 2$ anomaly
  
  Fayet, 2007 (direct coupling)  
  Pospelov, 2008 (kinetic mixing)

• Model building (Asymmetric DM models, . . . )
Dark Photon

- Kinetic mixing: $Z_d$ of $U(1)_d$ and $B$ of SM $U(1)_Y$  
  Holdom, 1986

$$\mathcal{L}_{\text{gauge}} = \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{\varepsilon}{2 \cos \theta_W} B_{\mu\nu} Z_d^{\mu\nu} - \frac{1}{4} Z_{d\mu\nu} Z_d^{\mu\nu}$$

$$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$$

- May be loop induced: $\varepsilon \sim e g_d / (4\pi)^2 \lesssim 10^{-3}$

- Remove cross term, via field redefinition
  - $B_\mu \rightarrow B_\mu + \frac{\varepsilon}{\cos \theta_W} Z_d\mu$; $Z-Z_d$ mass matrix diagonalization

$$\Rightarrow Z_d \text{ couples to EM current: } \mathcal{L}_{\text{int}} = -e \varepsilon J_{\mu\text{em}}^\mu Z_d^{\mu}$$

$$J_{\text{em}}^{\mu} = \sum_f Q_f \bar{f} \gamma^\mu f + \cdots$$

- Like a photon, but $\varepsilon$-suppressed couplings: "dark" photon
  - Neutral current coupling suppressed by $m_{Z_d}^2 / m_Z^2 \ll 1$

- Add $Z-Z_d$ mass mixing $\rightarrow Z_d$ as "dark" $Z$  
  HD, Marciano, Lee, 2012
  - "Dark" parity violation, rare meson and Higgs decays, \ldots
• Active experimental program to search for dark photon

Pioneering work by Bjorken, Essig, Schuster, Toro, 2009

• An early experimental target: $g_\mu - 2$ parameter space

GeV-scale visibly decaying $Z_d$ basically excluded as $g_\mu - 2$ explanation

S. Alekhin et al., arXiv:1504.04855 [hep-ph]
**“Invisible” Dark Photon**

- $\exists$ dark $X$ with $m_X < m_{Z_d}/2$ and $Q_d g_d \gg e\varepsilon \Rightarrow Br(Z_d \to X\bar{X}) \simeq 1$

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90% CL bound from BABAR Collaboration, arXiv:1702.03327 [hep-ex]

GeV-scale “invisible” dark photon $g_\mu - 2$ solution ruled out
Invisible $Z_d$ and DM Production

- Possible production and detection of DM beams in experiments
  - $p$ or $e$ on fixed target $\Rightarrow$ production of boosted $Z_d$ (meson decays, bremsstrahlung, ...)
  - $Z_d$ beam decays into DM which can be detected via $Z_d$ exchange
  - Event rate depends on $\alpha_d \equiv g_d^2/(4\pi)$ and $\varepsilon^2$

Batell, Pospelov, Ritz, 2009 ($p$ beam); Izaguirre, Krnjaic, Schuster, Toro, 2013 ($e$ beam dump)

S. Alekhin et al., arXiv:1504.04855 [hep-ph]

“Dark Matter Search in a Proton Beam Dump with MiniBooNE”
• “Semi-visible” dark photon decay

• May evade invisible boson searches

• $A' \rightarrow \chi_1 \chi_2$ with $\chi_2 \rightarrow \chi_1 e^+ e^-, \ldots$  
  Mohlabeng, to appear soon

• Could potentially be solution to $g_\mu - 2$ anomaly

Figure courtesy of E. Izaguirre
$\Delta = 0.4 \, m_{X_1}, \, m_{A'} = 3 \, m_{X_1}, \, \alpha_D = 0.1$

Figure courtesy of G. Mohlabeng
Some Alternative Possibilities for $g_\mu - 2$

- Gauged $L_\mu - L_\tau$: anomaly free
  Altmannshofer, Gori, Pospelov, Yavin, 1403.1269, 1406.2332

- Constrained by “trident processes” for low vector masses
  CCFR: Chicago-Columbia-Fermilab-Rochester; fixed target $E_\nu \sim 160$ GeV

Figures from 1406.2332
Moments from a Dark Higgs

Consider a GeV scale “dark” Higgs $\phi$ as main source of $g_\mu - 2$

Potentially associated with $U(1)_d$ breaking

Effective coupling of $\phi$ with leptons:

$$\mathcal{L}_{\phi\ell\ell} = -\phi\bar{\ell}(\lambda_S^\ell + i\lambda_P^\ell\gamma_5)\ell$$

$\ell = e, \mu, \tau$, and $\lambda_S^\ell$ ($\lambda_P^\ell$) CP-even (odd) coupling

Induced by heavy vector-like fermions (integrated out at $E \sim m_\mu$)

[Alternate model: $\phi$-Higgs mixing (leptonic 2HDM)

Batell, Lange, McKeen, Pospelov, Ritz, 1606.04943]
\(\mu\)-EDM, assuming \(a_\mu \pm 1\sigma; \tan \theta_\ell = \lambda_\ell^\ell / \lambda_S^\ell\)

Various experimental implications:

- Direct probes: bump hunting in \(\mu\) decay and capture, \(K\) decay including a \(\mu\)
- Potentially observable muon EDM \(\lesssim 10^{-22} \text{ e cm}\) \(\text{Semertzidis et al., 2000, 2003}\)
- Current bound \(|d_\mu| < 1.8 \times 10^{-19} \text{ e cm}\) \(\text{Muon (g-2) Collaboration, 2008}\)
- Possible lepton flavor violating decays, deviation in \(\text{BR}(H \rightarrow \mu^+\mu^-)_{\text{SM}}\)
• Axion-Like Particles
  Marciano, Masiero, Paradisi, Passera, 1607.01022
• Pseudo-scalar $a$: $\mathcal{L}_a = \frac{1}{4} g_{a\gamma\gamma} a \, F_{\mu\nu} \tilde{F}^{\mu\nu} + i y_{al} a \bar{l} \gamma_5 l$

  \[ [\mathcal{L}_s: (\tilde{F}, g_{a\gamma\gamma}, iy_{al}, \gamma_5) \rightarrow (F, g_{s\gamma\gamma}, y_{sl}, 1)] \]

• “Barr-Zee” diagram (B) or LBL (C):
  $a_{BZ,a,s} \propto g_{a\gamma\gamma} y_{al}$; $a_{LBL,a} \propto -a_{LBL,s} \propto g_{a\gamma\gamma}^2$
• $g_{\mu} - 2$: $y_{al} g_{a\gamma\gamma} > 0$; $g_{a\gamma\gamma} \sim 10^{-(2-4)} \text{ GeV}^{-1}$
• $g_{a\gamma\gamma}$ large; can be experimentally allowed
See Bauer, Neubert, Thammm, 1708.00443, for a detailed discussion of constraints

- May require non-trivial model building
  Marciano, Masiero, Paradisi, Passera, 2016

• VP contribution (D) small

Figures from 1607.01022
**A New Twist**

- Improved $\hbar/M_{\text{Cs}}$ measurements using matter-wave interferometry

$$\Rightarrow \alpha^{-1}(\text{Cs}) = 137.035999046(27) \quad \text{Parker et al., 2018}$$

$$\Delta a_e \equiv a_e^{\text{exp}} - a_e^{\text{SM}} = [-87 \pm 28 \,(\text{exp}) \pm 23 \, (\alpha) \pm 2 \,(\text{theory})] \times 10^{-14}$$

$$\Rightarrow \Delta a_e = (-87 \pm 36) \times 10^{-14}$$

- A 2.4$\sigma$ discrepancy, opposite sign to $\Delta a_\mu$
- Does not follow naive mass scaling: $(\Delta a_e/\Delta a_\mu)(m_\mu/m_e)^2 \sim \mathcal{O}(10)$
- Previous best value of $\alpha \rightarrow \Delta a_e = (-130 \pm 77) \times 10^{-14}$ (1.7$\sigma$ effect)
- Further improved $\alpha$ and $g_e - 2$ measurements needed for more robust conclusions
- We will next describe a minimal low scale model for both $\Delta a_\mu$ and $\Delta a_e$

See also:

Crivellin, Hoferichter, Schmidt-Wellenburg, 1807.11484:
Focuses on EFT analysis and some Type (A) models

Liu, Wagner, Wang, 1810.11028:
Complex scalar, light pseudo-scalar coupling to electron, scalar coupling to muon
A Minimal Model for $\Delta a_{\mu,e}$ Discrepancies

H.D., Marciao, 1806.10252

- Note: simple “dark photon” models $\rightarrow \Delta a_\ell > 0$; cannot work
- Consider a real scalar (not necessarily associated with symmetry breaking):

$$\mathcal{L}_\phi = -\frac{1}{2} m_\phi^2 \phi^2 - \sum_f \lambda_f \phi \bar{f} f - \frac{\kappa_\gamma}{4} \phi F_{\mu\nu} F^{\mu\nu}$$

- Fermion $f$ could be from or beyond SM
- We focus on $2m_\mu \lesssim m_\phi \lesssim$ few GeV; relevant to low energy probes
- Mainly consider 1-loop $\Delta a_\mu$ and 2-loop (Barr-Zee) for $\Delta a_e$

- Effective $\phi \gamma \gamma$ coupling from heavy fermion loop ($\bullet$ in the diagram)
• At 1-loop (self energy): \( \Delta a_\ell = \frac{\lambda_\ell^2}{8\pi^2} x^2 \int_0^1 dz \frac{(1+z)(1-z)^2}{x^2(1-z)^2+z} \)
For a lepton \( \ell \) of mass \( m_\ell \) and \( x \equiv m_\ell/m_\phi \)

• At 2-loop (Barr-Zee): \( \Delta a_B^\ell(f) = -\frac{\alpha}{6\pi} m_\ell \frac{\lambda_\ell \lambda_f}{\pi^2} Q_f^2 N_c f I(y) \) (leading order in \( m_\ell \))
where \( I(y) = \frac{3}{4} y^2 \int_0^1 dz \frac{1-2z (1-z)}{z(1-z)-y^2} \ln \frac{z(1-z)}{y^2} \) \( (y \equiv m_f/m_\phi) \)

• We set \( m_\phi = 250 \text{ MeV} \) \( \Rightarrow \Delta a_\mu \) with \( \lambda_\mu = 10^{-3} \)

• Using dark photon constraints as a guide: \( \lambda_e \lesssim 4 \times 10^{-6} \); we set \( \lambda_e = 4 \times 10^{-6} \)

• With the above parameter, BZ fermion loop contributions to \( \Delta a_e \)
  
  Muon: \( -5(\lambda_\mu/10^{-3}) \times 10^{-14} \)
  - Accounts for \( \sim 6\% \) of \( \Delta a_e \)

  Tau: \( -14(\lambda_\tau/10^{-2}) \times 10^{-14} \)
  - Explain \( \Delta a_e \) for \( \lambda_\tau \approx 0.06 \) (large but not ruled out)

  - Promising search at BaBar, Belle, Belle II: \( e^+e^- \rightarrow \tau^+\tau^-\phi \rightarrow \tau^+\tau^-\ell^+\ell^- \)

    See e.g. Batell, Lange, McKeen, Pospelov, Ritz, 1606.04943

TeV scale fermion: \( -7.5\lambda_{\text{TeV}} \times 10^{-14} \)
- Requires \( O(10) \) charged fermions with \( O(1) \) coupling
Concluding Remarks

• Currently, the long-standing $\sim 3.7\sigma$ deviation of $g_\mu - 2$ one of the most significant potential hints for new physics

• The new E989 experiment at Fermilab underway to settle the status of this anomaly; a future JPARC experiment could be a valuable confirmation (very different setup)

• Models with new physics both around weak scale and $\lesssim$ GeV have been invoked to address this possible signal of new phenomena

• High scale models (Type A), usually extension of the SM, currently being probed and constrained at the LHC

• Low scale models (Type B) typically more minimal and often invoke a sequestered dark sector with feeble couplings to the SM; subject of intense experimental and phenomenological investigations

• New twist: the recent $\alpha$ determination suggests $\Delta a_e < 0$ at $\sim 2.4\sigma$

• A minimal model with a real scalar at low energies seems to be able to explain both $\Delta a_\mu$ and $\Delta a_e$

• Good news: both theory and experiment are moving towards a more decisive conclusion on $g_\mu - 2$ (and perhaps $g_e - 2$) over the next few years