Reviving the Dark Photon Explanation of the Muon g-2 Anomaly

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Main point of this talk

- Show that Inelastic dark matter with large mass splittings revives the dark photon explanation of the \((g_\mu - 2)\) anomaly

- Model gives displaced lepton signature we can search for at current beam dumps and low energy colliders
Current Status of Particle Physics

Evidence of particle physics phenomena not explained in SM points to need for *New Physics*.

One of the many ways *New Physics* may manifest:

**Indirectly: as deviations from SM predicted processes**

NP may show up in here

⇒ Anomalous magnetic moments
\[ \Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM} \]
\[ = (28.1 \pm 3.6_{th} \pm 6.3_{exp}) \times 10^{-10} \]

3.3 - 3.6 \sigma discrepancy

3.6σ simply not enough to celebrate New Physics

very exciting period for g-2

Fermilab E989 experiment is currently running

More precise measurement and significant reduction in theory uncertainty could mean New Physics contribution

SM theory computation is improving
Focus for this talk: **Dark Photon** $A'$

Massive gauge boson in U(1)' extension of SM

$$\mathcal{L} \supset \frac{m_{A'}}{2} A'_\mu A'^\mu + g_D \bar{\psi}_D \gamma_\mu A'^\mu \psi_D + \epsilon e \bar{\psi}_{s\nu} \gamma_\mu A'^\mu \psi_{s\nu}$$

Coupling to visible

**Kinetic mixing with SM photon**

Contribution to $g-2$

$$a_\mu = \frac{\alpha \epsilon^2}{2\pi} \int_0^1 dz \frac{2m_\mu^2 z (1 - z)^2}{m_\mu^2 (1 - z)^2 + m_{A'}^2 z}$$

Favored to explain muon g-2

\[ e e \bar{\psi}_{sm} \gamma_{\mu} A_\mu' \psi_{sm} \]

Coupling to visible sector been searched for
Invisible Decay

\[ g_D \bar{\psi}_D \gamma_\mu A'_\mu \psi_D \]

Favored to explain muon g-2


What if Majorana mass is small but NOT zero??

Diagonalizing from gauge basis to mass basis:

$$\psi_D = (\eta \quad \xi^\dagger) \rightarrow \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}$$

Pseudo-Dirac fermions

$$\mathcal{L} \supset g_D \bar{\chi}_2 \gamma_\mu A'^\mu \chi_1 + m_D \bar{\chi}_2 \chi_1 + h.c$$

With mass splitting

$$\Delta \equiv m_2 - m_1$$

$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$

Heavier state decay into lighter state & SM states
If $\chi_2$ decays inside detector $\Rightarrow$ soft displaced leptons

We can look for these displaced tracks at colliders and beam dumps

Izaguirre, Krnjaic & Shuve: *Phys.Rev.* D93 (2016) no.6, 063523


Can dark photon still explain muon g-2?


Signatures @ Electron Beam Dumps
(quasi) elastic scattering & decays

$e^-$

Beam

$e^-$

Dump

$e^-$

Dirt

$\chi$

Detector

$A'$ production modes

- Dark Bremstrahlung

E137 (SLAC 1988)

E $\sim$ 20 GeV, 1e20 EOT

$\sim$ 400 m baseline, no BG

BDX (JLab 2020?)

E $\sim$ 11 GeV, 1e22 EOT

$\sim$ 20 m baseline, few BG evts.
**Signatures @ B-Factories**

mono photon + missing energy

Signatures from displaced vertices and/or missing energy

\[
\begin{align*}
& e^+ \\
\rightarrow & & e \\
\rightarrow & & \gamma \\
& e^- \\
\rightarrow & & A' \\
\rightarrow & & \chi_1 \\
\rightarrow & & \chi_0
\end{align*}
\]

**BABAR**
- \(E \sim 10.5 \text{ GeV}\)
- \(L \sim 53 \text{ fb}^{-1}\)

**BELLE II**
- \(E \sim 11 \text{ GeV}\)
- \(L \sim 50 \text{ ab}^{-1}\) by 2025


Inelastic dark Matter - $\chi_1$ is thermal relic

Whose relic abundance is set by:

Coannihilation

Downscattering

Decay
Can dark photon still explain muon g-2?

Its possible BaBar could have vetoed lepton events in their invisible decay search

Belle II: With dedicated mono-photon trigger, search for Invisible & semi-visible events
For what splittings can we still explain g-2

\[ \alpha_D = 0.5, \ m_{A'} = 3 \ m_{\chi_1}, \ \epsilon = \epsilon_{g\mu-2} \]

\[ \Delta > m_{A'} - 2 \ m_{\chi_1} \]

**Summary**

- Leptonic moments are exquisite probes of new physics

- Dark Photon coupling elastically to dark fermions robustly ruled out in muon g-2 explanation

- Dark Photon coupled inelastically to dark fermions:
  - Continues to explain muon g-2 anomaly
  - Simultaneously explains dark matter relic abundance
  - Gives displaced lepton signature to search for

- Available region of space can also be probed by:
  - Current: MiniBooNE, Nova & NA64
  - Future: LDMX, BDX, SeaQuest & FASER
Thanks for your Attention
Back up Slides
Electron magnetic moment one of the most accurately verified predictions in nature

**Theory:** Calculated up to 10th order in QED

**Experiment:** Measured with very high precision at Harvard using cylindrical Penning trap

\[ \Delta a_e \equiv a_e^{exp} - a_e^{SM} = -84 \pm 36 \times 10^{-14} \]

Giving a \(-2.3\sigma\) discrepancy

F. Jegerlehner, arXiv:1804.07409v2
Signatures @ Proton Beam Dumps
(quasi) elastic scattering & decays

A' production modes
- neutral meson decay
  LSND (2001)
  E ~ 800 MeV, 1e24 POT
- Dark Bremstrahlung
  MiniBooNE (2017)
  E ~ 9 GeV, 1e20 POT


deNiverville, Chen, Pospelov, Ritz, Phys.Rev. D95 (2017) no.3, 035006

Batell, deNiverville, McKeen, Pospelov, Ritz, Phys.Rev. D90 (2014) no.11, 115014

Ezaguirre, Kahn, Kmijaic, Moschella, Phys.Rev. D96 (2017) no.5, 055007
The text contains a discussion about the production of dark matter (DM) through inelastic processes at electron and proton beam dump experiments and fixed-target experiments. The text describes the signatures that can be observed in the detector, such as recoiling electrons with missing energy and mass, and the use of active targets to verify beam interactions. The text also introduces a class of models of coannihilating DM, where DM couples inelastically to the Standard Model through a kinetically-mixed dark photon. It details the early universe cosmology and freeze-out of the model, and presents a useful parametrization of the parameters of the model in which the thermal target is largely an invariant under variation of couplings and of mass hierarchies.

**Signatures @ Missing Momentum Experiments**

- **LDMX**
  - \( E \sim 8 \text{ GeV} \)
  - \( \sim 3 \times 10^{16} \) EOT
  - \( \sim 0.1 \text{ rad. length} \)
  - thin target

- **NA64**
  - \( E \sim 100+ \text{ GeV} \)
  - \( \sim 1 \times 10^{11} \) EOT
  - \( \sim 2 \text{ m thick target} \)

For what couplings can we still explain $g-2$?