Dark Matter Muon Anomalous Magnetic Moment and the XENON1T Excess

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A Very Economic Model

- **DM candidate**
- **Xenon1T Excess**
- **Muon g-2**
- **3 scalars**
- **Collider and other terrestrial constraints**
- **Cosmological constraints**
- **Testability at future experiments**

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The XENON1T Excess
Overview of the Model
Muon Anomalous Magnetic Moment
Constraints on $y_\mu$ and $y_e$
Explanation of the Excess
Dark Matter Relic Density
Cosmological Constraints
Conclusion
The XENON1T Excess

- An excess in the electronic recoil events, prominent between 2 and 3 keV at the XENON1T detector was reported earlier this year [2006.09721]
Overview of the Model

- complex scalar field $\phi$
- real scalar field $\omega$
- Scalar potential

$$V_{\phi,\omega} \equiv \mu_\phi^2 \phi^* \phi + (\Delta^2 \phi^2 + H.c.) + 2\mu_\phi \omega \phi^* \phi \omega + [(A_1 + iA_2) \phi^2 + H.c.] \omega .$$

- Presence of the $\Delta^2$ term serves to split the two components of $\phi \equiv (\phi_2 + i\phi_1)/\sqrt{2}$

$$m_{2,1} = \sqrt{\mu_\phi^2 \pm 2\Delta^2} = \mu_\phi \pm \delta_m$$

$$\delta_m \simeq \Delta^2 / \mu_\phi$$
The soft trilinear terms in scalar potential engender couplings of the form $g_{ij}\phi_i\phi_j\omega$, with

$$g_{11} = \mu \phi - A_1, \quad g_{22} = \mu \phi + A_1, \quad g_{12} = -2A_2$$

leptophilic $\omega$, couples to fermions through dimension-five operators such as

$$\mathcal{L}_{\text{int}} \ni (\omega/\Lambda) H \left[ \tilde{\nu}_\mu \bar{L}_2 \mu_R + \tilde{\nu}_e \bar{L}_1 e_R \right] + H.c.,$$

lead to effective Yukawa terms

$$\mathcal{L}^{\text{eff}}_{\text{Yuk}} \ni \omega \left[ y_\mu \bar{\nu}_\mu \mu + y_e \bar{\nu}_e e \right], \quad y_\ell \equiv \tilde{y}_\ell v / \sqrt{2}\Lambda$$

parametrize $y_e$ as

$$y_e = n_s \left( m_e / m_\mu \right) y_\mu$$

scaling factor $n_s = \mathcal{O}(1)$
Muon Anomalous Magnetic Moment

- Discrepancy in muon $g-2$ [10.1103/PhysRevD.98.030001]

\[ \delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (261 \pm 63 \pm 48) \times 10^{-11}, \]

- Contribution to $a_\mu$ in the model, in addition to SM,

\[ \delta a_\mu = \frac{y_\mu^2 m_\mu^2}{8\pi^2} \int_0^1 \frac{z^2 (2 - z) dz}{m_\omega^2 (1 - z) + m_\mu^2 z^2} \]
Figure: The $2\sigma$ band favoured by $(g-2)_\mu$ and the constraint from the $4\mu$ final state assuming $Br(\omega \rightarrow \mu^+\mu^-) = 1.0$. The dotted curve is the projection from BELLE-II experiment.
Figure: Constraints on the mediator \( \omega \) coupling to electron. The dotted curves indicate projected sensitivities from HPS and Belle-II.
With the effective Yukawa couplings in place, the triple scalar vertices give rise to three distinct DM initiated processes at a detector, namely $\phi_i D \rightarrow \phi_i D$ (where $D$ is a detector entity, nucleus or electron) and $\phi_2 D \rightarrow \phi_1 D$

- former are elastic in nature with the typical recoil energy for an electron being $\mathcal{O}(\text{eV})$ and thus, unable to explain the recoil-energy profile
- the $g_{12}$ term that causes inelastic scattering off the electron can lead to such events provided the mass-splitting $\delta_m \sim \mathcal{O}(\text{keV})$
Event rate $R$ is determined as

$$\frac{dR}{dE} = N_T \frac{\rho_{\phi_2}}{m_2} \frac{d\langle \sigma v \rangle}{dE}$$

Where

$$d\langle \sigma v \rangle = \frac{a_0^2 \bar{\sigma}_e}{2m_e} \int_{v_{\text{min}}}^{v_{\text{max}}} dv \frac{f(v)}{v} \int_{p_-}^{p_+} p dp |F_{\phi}(p)|^2 K(E, p)$$

For free electron scattering proceeding through $\omega$-exchange,

$$\bar{\sigma}_e = y_e^2 g_{12}^2 m_e^2 / (4\pi m_\omega m_\phi^2)$$
Figure: $g_{\omega\phi\phi} \equiv g_{12}$ values satisfying the XENON1T excess (green) and relic density (red), as a function of $m_\omega$. 
DM comprises equal parts of $\phi_{1,2}$

$\omega$ serves as a portal between the dark and the ordinary sectors

Smallness of the splitting allows the heavier DM component to be stable on cosmological time scales

For very light $\phi_i$, the only channel available is $\phi_i\phi_j \rightarrow e^+e^-$, where the two scalars could either be the same or different

For heavier $\phi_i$, the $\mu^+\mu^-$ and the $\omega\omega$ modes open up
Constraints arising from energy injections into the CMBR are evaded by introducing a third scalar field $\eta$ to which the mediator $\omega$ dominantly decays into. While $\eta$ itself is cosmologically stable, its interactions drive its relic density to less than $\mathcal{O}(10^{-3})$. 
Competing constraints render the model eminently testable and, thus, interesting.

Upcoming Belle-II and the Heavy Photon Search (HPS) experiments will be able to probe parameter space for $m_\omega \sim 200 \text{ MeV-3 GeV}$

A similar Belle-II projection for $y_\mu$ exists for $m_\omega \sim 20 \text{ MeV-1 GeV}$

The FASER experiment too can probe such parameters.
Conclusion

- A very economical model: only three extra scalar fields
- Simultaneously explains the XENON1T excess (through inelastic DM scattering), as well as the anomalous magnetic moment of the muon while producing the requisite dark matter relic density
- A sufficient parameter space exists satisfying all constraints, experimental (beam dumps, colliders etc) astrophysical (stellar cooling) and cosmological (BBN, $N_{\text{eff}}$)
- A large part of the favoured parameter space would be testable in the near future both in terrestrial experiments as well as CMBR observations
Thank You!