A last chance for kinetic mixing: explaining $(g-2)_\mu$ with semi-visible dark photons

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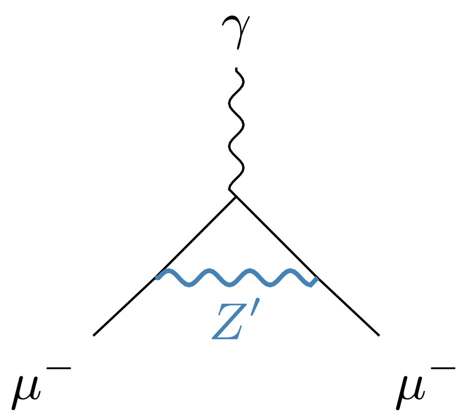
Introduction

The Fermilab E989 experiment has recently released the new measurement of the anomalous magnetic moment of the muon $a_\mu = (g_\mu - 2)/2$ [1]. That has confirmed the long-standing anomaly first observed by the E821 experiment at the Brookhaven National Laboratory more than 15 years ago [2]. The new result has further improved the significance of the deviation from the theoretical calculations:

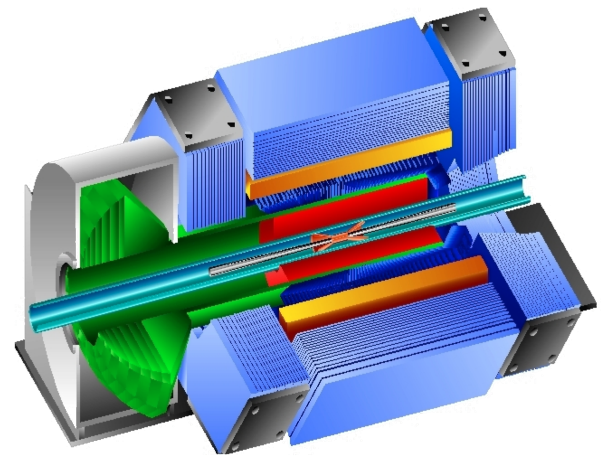
$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{th}} = (2.51 \pm 0.59) \times 10^{-9}\,.$$

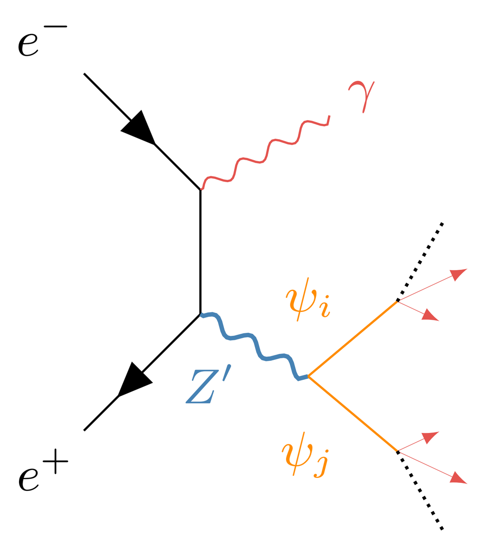
An explanation based on dark sector theories is an exciting solution. In particular, a one-loop contribution given by a dark photon with kinetic mixing to the Standard Model would provide an elegant result. However, searches for both visible and invisible dark photon decays have already excluded this possibility. A viable scenario is represented by semi-visible decays, as the previous bounds can be relaxed [3]. For instance, the produced dark photon may decay in dark sector particles, which may eventually decay int Standard Model particles. This opens region a of the parameter space able to describe the anomaly, with $m_{Z'} \approx 0.3 \div 1.3$ GeV and $\varepsilon \approx 10^{-3} \div 10^{-2}$. We will consider models with the dark photon coupling to dark fermions, reinterpreting the bounds of invisible decaying dark photon. In all generality, the lagrangian will be characterised by a new *dark* symmetry $\mathrm{U}(1)'$, with new dark states labelled by ψ_i. The dark photon Z' would be able to decay into $\psi_i\psi_j$ and we would also have the decay $\psi_j \to \psi_i\, \ell^+ \ell^-$, with $m_j > m_i$.



BaBar constraints

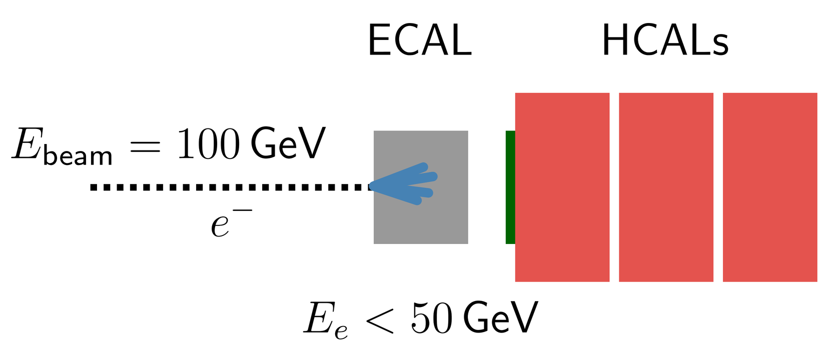
Invisible dark photon searches in the collider BaBar are based on initial state radiation of the dark photon from the incoming electron, accompanied by missing energy [4]. If dark photon decays semi-visibly, additional tracks are vetoed in the selection and the constraints get weakened.

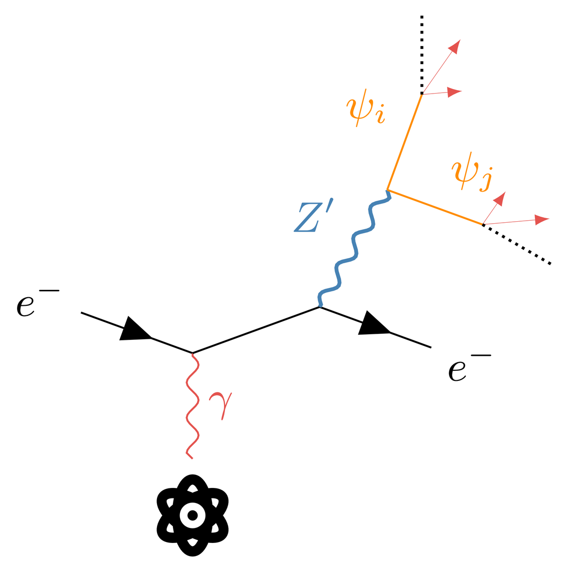




NA64 constraints

Invisible dark photon searches in the beam dump NA64 are based on the measurement of missing energy due to dark photon bremsstrahlung from an electron of the beam [5]. If the dark photon semi-visible decays happen promptly, they will often not be vetoed by the analysis. Indeed, NA64 is still sensitive to additional decay products contained in the primary electron shower.





NA64 has also performed searches for semi-visible decays of dark photon. They looked for energy deposition in the HCAL [6].

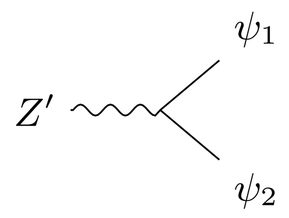
Model 1: Inelastic dark matter (one pseudo-Dirac pair) [3]

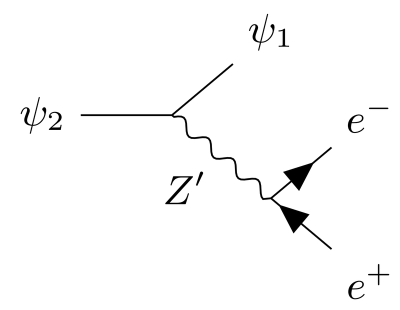
We consider two oppositely charged Majorana fermions:

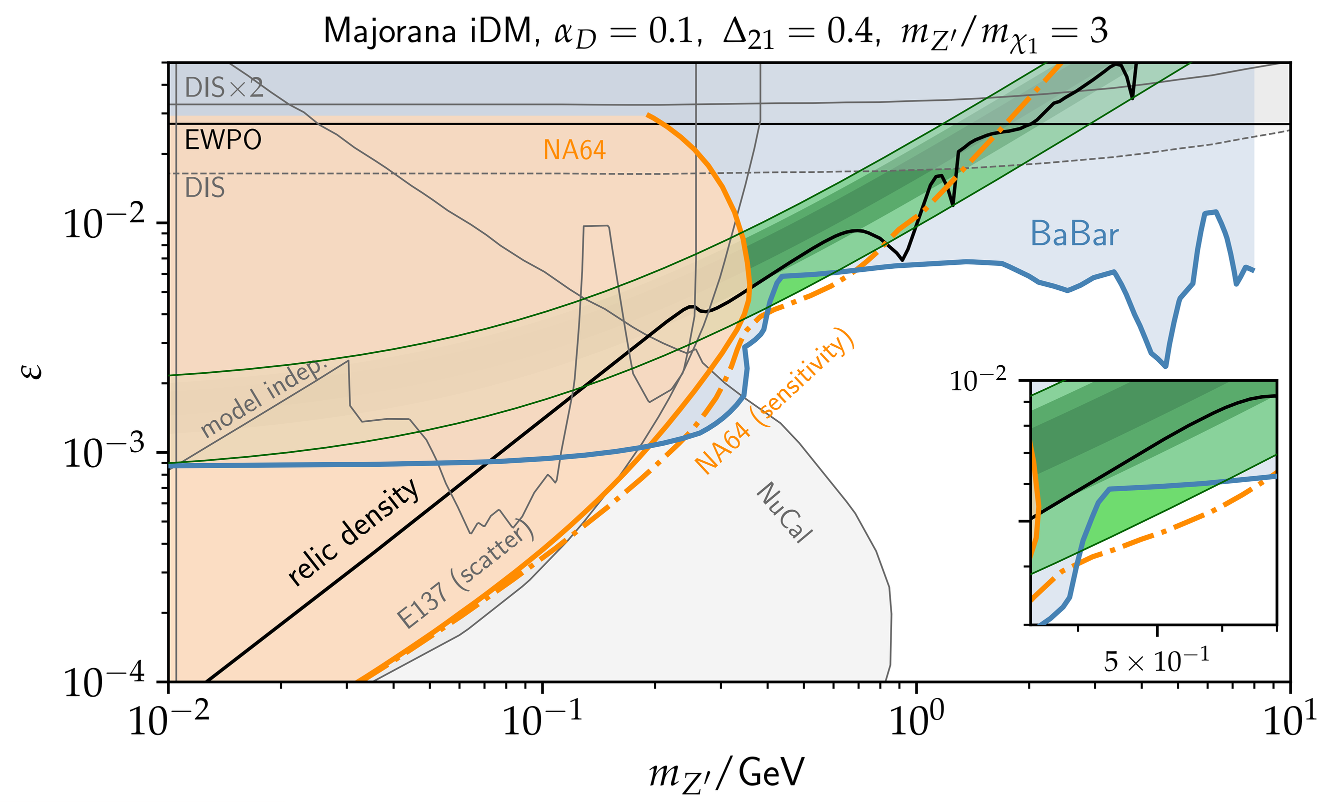
$$\mathcal{L} \supset \frac{1}{2}\begin{pmatrix}\overline{\psi_{\mathrm{L}}} & \overline{\psi_{\mathrm{R}}^c}\end{pmatrix}\begin{pmatrix}\mu_{\mathrm{L}} & m_{\mathrm{D}}\\ m_{\mathrm{D}} & \mu_{\mathrm{R}}\end{pmatrix}\begin{pmatrix}\psi_{\mathrm{L}}^c & \psi_{\mathrm{R}}\end{pmatrix} + \text{h. c.}$$

with $\mu_{\mathrm{L}} \approx \mu_{\mathrm{R}} \ll m_{\mathrm{D}}$, so that on-diagonal couplings result suppressed. After mass matrix diagonalisation, we obtain ψ_1 and ψ_2 with mass splitting $\Delta_{12} = (m_1 - m_2)/2$. We have ψ_1 stable, which could be dark matter candidate, with relic density given by coannihilations. The interaction lagrangian is:

$$\mathcal{L} \supset g_{\mathrm{D}}\overline{\psi}_1 Z' \psi_2\,.$$







The model is excluded at 2σ by BaBar and NA64.

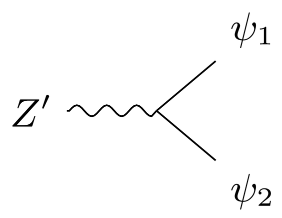
Model 2: Inelastic dark matter (several pseudo-Dirac pairs)

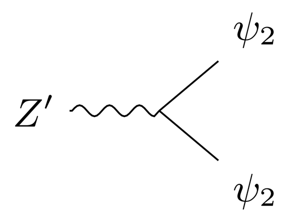
We consider a neutral (η) and a charged (χ) - under $\mathrm{U}(1)'$ - pseudo-Dirac pairs (small Majorana masses):

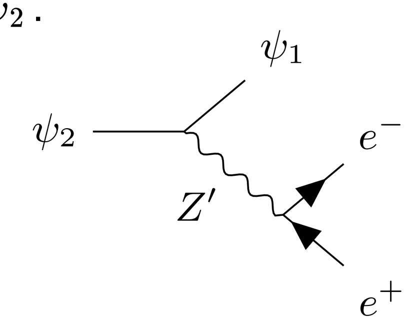
$$\mathcal{L} \supset \begin{pmatrix}\eta_{\mathrm{L}} & \chi_{\mathrm{R}}\end{pmatrix}\begin{pmatrix}M_1 & M_{\mathrm{L}}\\ M_{\mathrm{R}} & M_2\end{pmatrix}\begin{pmatrix}\eta_{\mathrm{R}}\\ \chi_{\mathrm{R}}\end{pmatrix} + \text{h. c.}$$

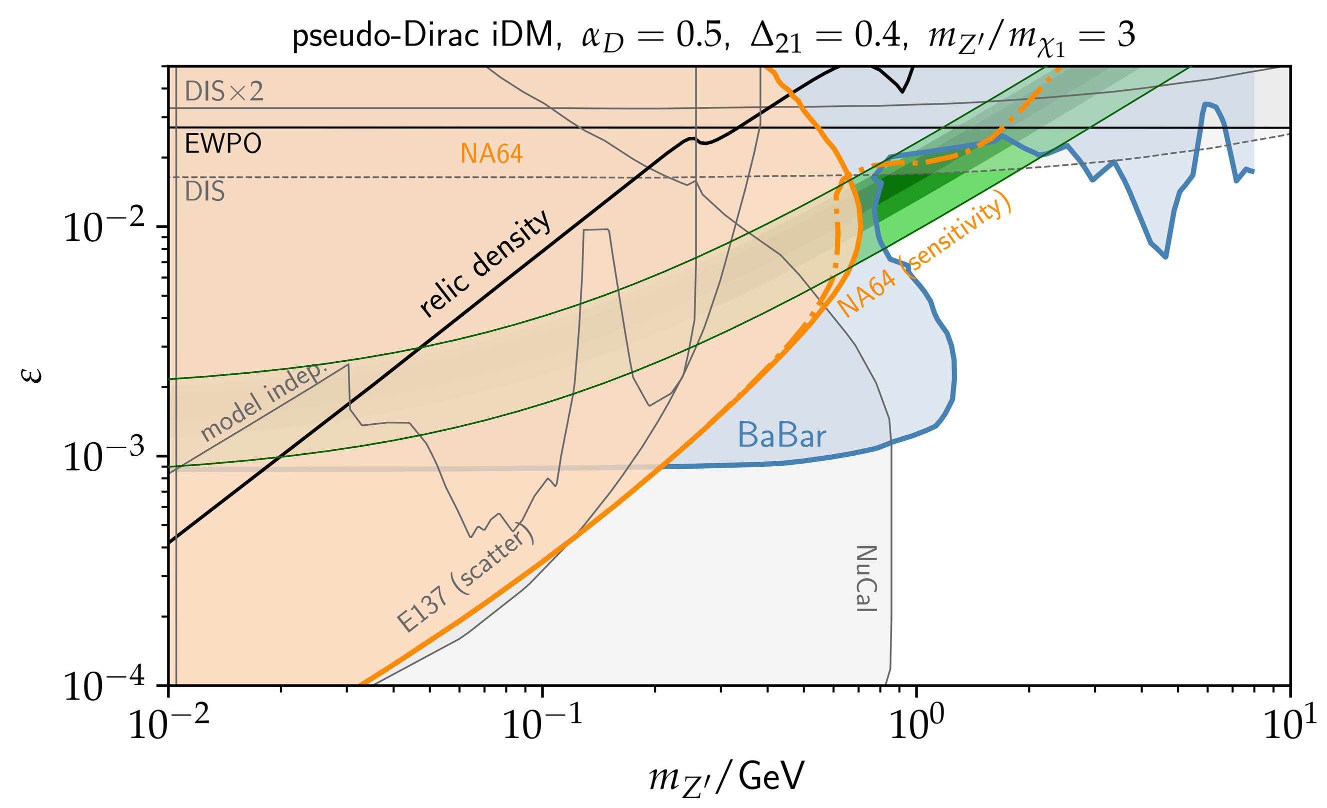
After mass matrix diagonalisation, we obtain a light neutral state ψ_1, which could be a dark matter candidate and an heavier state ψ_2 more strongly coupled to dark force, with small mixing θ:

$$\mathcal{L} \supset g_{\mathrm{D}}\theta^2\,\overline{\psi_1} Z' \psi_1 + g_{\mathrm{D}}\theta\,\overline{\psi_2} Z' \psi_1 + g_{\mathrm{D}}\overline{\psi_2} Z' \psi_2\,.$$









The model can explain $(g_\mu - 2)$. However, ψ_1 can't be dark matter, unless it has secluded annihilations.

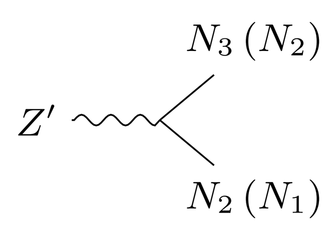
Model 3: Heavy neutral leptons [7]

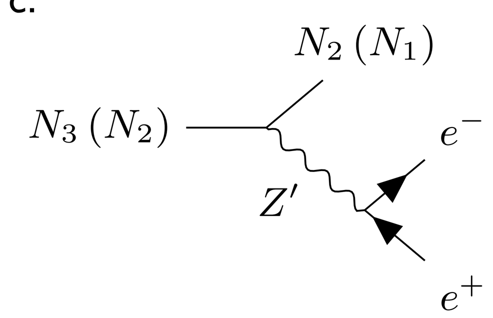
Consider the dark states mixing with neutrinos, a minimal model with a sterile neutrino N and a pair of fermions charged under $\mathrm{U}(1)'$ will be given by:

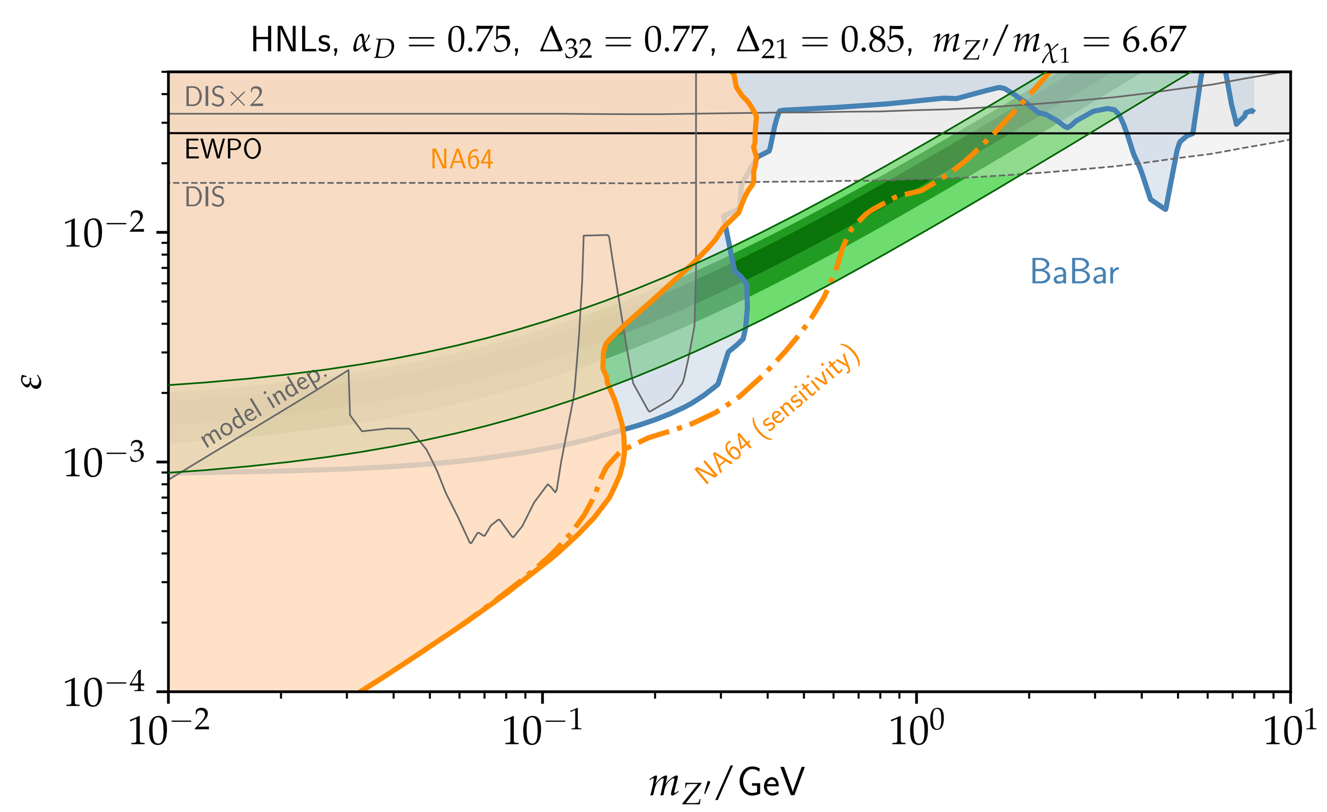
$$\begin{pmatrix}M_N & \Lambda_{\mathrm{L}} & \Lambda_{\mathrm{R}}\\ \Lambda_{\mathrm{L}}^T & 0 & M_X\\ \Lambda_{\mathrm{R}}^T & M_X^T & 0\end{pmatrix}\begin{pmatrix}N\\ \psi_{\mathrm{L}}\\ \psi_{\mathrm{R}}\end{pmatrix}$$

And the interaction vertices would be encoded in:

$$\mathcal{L} \supset g_{\mathrm{D}} V_{ij}\overline{\psi}_i Z' \psi_j + \text{h. c.}$$







The model can explain $(g_\mu - 2)$.

References

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