Implications of a Running Dark Photon Coupling

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For an "invisible" dark photon Z_d that dominantly decays into dark states, the running of its fine structure constant α_d with momentum transfer $q > m_{Z_d}$ could be significant. A similar running in the kinetic mixing parameter ε^2 can be induced through its dependence on $\alpha_d(q)$. The running of couplings could potentially be detected in "dark matter beam" experiments, for which theoretical considerations imply $\alpha_d(m_{Z_d}) \lesssim 0.5$.

The following is a summary of a talk - entitled "Running in the Dark Sector" - given by the author at the 11^{th} Patras Workshop on Axions, WIMPs and WISPs, held at the University of Zaragoza, Spain, June 22-26, 2015. The presentation is based on the work in Ref.[1], where a more complete set of references can be found.

The possibility of a dark sector that includes not only dark matter (DM), but also dark forces and other states has attracted a great deal of attention in recent years [2]. In particular, it has been noted that a "dark photon" Z_d of mass $m_{Z_d} \lesssim 1$ GeV, mediating a dark sector $U(1)_d$ force may explain potential astrophysical signals of DM [3]. It is often assumed that the Z_d can couple to the electromagnetic current of the Standard Model (SM) via a small amount of kinetic mixing ε [4] (though it may have other couplings as well [5]) which can be naturally loop induced: $\varepsilon \sim e g_d/(16\pi^2)$ [4] where e and g_d are the electromagnetic and $U(1)_d$ coupling constants, respectively. The $3.5\,\sigma$ muon $g-2$ anomaly [6] may potentially be explained by a light ($m_{Z_d} \lesssim 0.1$ GeV) Z_d with $\varepsilon \sim 10^{-3}$ [7].

If there are dark states, such as DM, that have $U(1)_d$ charge $Q_d \neq 0$ and have a mass $m_d < m_{Z_d}/2$, then they will likely be the dominant decay channels for Z_d, making it basically invisible. This possibility can be employed to form beams of light (sub-GeV) DM that may be detectable in fixed target experiments (whose detection in nuclear recoil experiments would be challenging). The basic idea is that an intense beam of protons or electrons impinging on a target (or beam dump) can lead to production of boosted Z_d particles that decay in flight mostly into light DM states, generating a "DM beam" which can be detected via Z_d-mediated scattering from atoms [8, 9]. See Figure 1 for a schematic illustration of such a setup. The production rate of on-shell dark photons is controlled by $\alpha\varepsilon^2$, while the detection of the DM particles is governed by $\alpha_d\alpha\varepsilon^2$, where $\alpha \equiv e^2/(4\pi)$ and $\alpha_d \equiv g_d^2/(4\pi)$.

If the above light DM particles are thermal relics, one expects [8, 9]

$$\alpha_d \sim 0.02\, w \left(\frac{10^{-3}}{\varepsilon}\right)^2 \left(\frac{m_{Z_d}}{100\text{ MeV}}\right)^4 \left(\frac{10\text{ MeV}}{m_d}\right)^2 , \tag{1}$$

where $w \sim 10$ for a complex scalar [8], and $w \sim 1$ for a fermion [9]. As experiments probe smaller values of ε, one could start probing $\alpha_d \sim 1$, which in the presence of light DM with $Q_d \neq 0$ can lead to significant running of α_d. As the fixed target experiments (Figure 1) probe

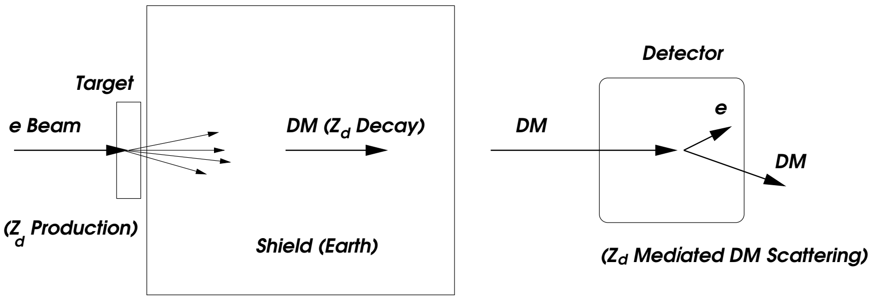

Figure 1: Schematic illustration of a fixed target "Dark Matter beam" experiment, using an electron beam.

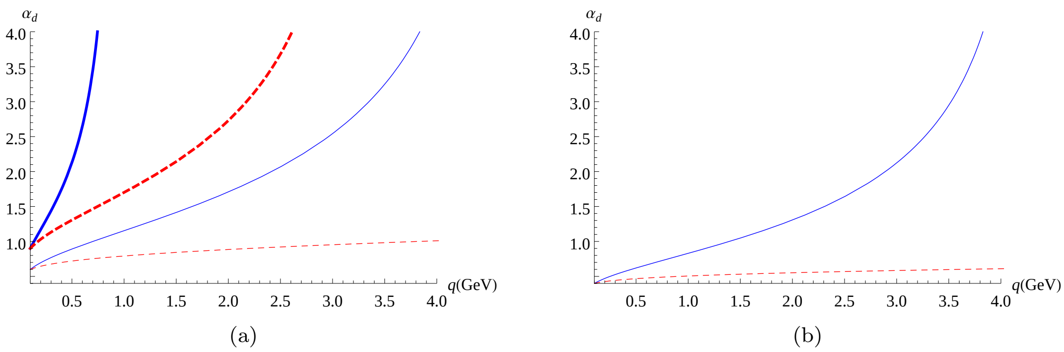

Figure 2: Running of $\alpha_d(q)$, with (a) one DM particle, where the thin (thick) lines correspond to $\alpha_d(q_0) = 0.6$ (0.9), and (b) two DM states with $\alpha_d(q_0) = 0.4$. The solid (dashed) lines correspond to fermion (scalar) DM states. In both cases, the contribution from a dark Higgs particle is included, $q_0 = 0.1$ GeV, and $m_{Z_d} \lesssim q_0$ is assumed.

momentum transfer values in the GeV range, *i.e.* $q^2 \gg m_{Z_d}^2$, the effect of running on the event rate can be significant and it may even lead to unreliable predictions for $\alpha_d(q^2) \gg 1$. To illustrate these points, we will consider n_F fermions and n_S scalars with $|Q_d| = 1$, all below m_{Z_d}. We will assume that the mass of Z_d is generated by a dark Higgs scalar and hence $n_S \geq 1$ in our analysis.

We will employ a 2-loop beta function for $U(1)_d$

$$\beta(\alpha_d) = \frac{\alpha_d^2}{2\pi}\left[\frac{4}{3}\left(n_F + \frac{n_S}{4}\right) + \frac{\alpha_d}{\pi}(n_F + n_S)\right], \tag{2}$$

where $\beta(\alpha_d) \equiv \mu\, d\alpha_d/d\mu$, with μ, the renormalization scale, set by the relevant momentum transfer q. The reference infrared momentum transfer is taken to satisfy $q_0 \gtrsim m_{Z_d}$ and we will ignore the mass of Z_d in what follows. The form of $\beta(\alpha_d)$ in the above suggests that perturbative control is lost when $\alpha_d \gtrsim \pi$.

In Figures 2 (a) and (b), we have presented the effect of running for various values of α_d and one and two DM states, respectively. We see that for values of $\alpha_d \lesssim 1$ the running effect can

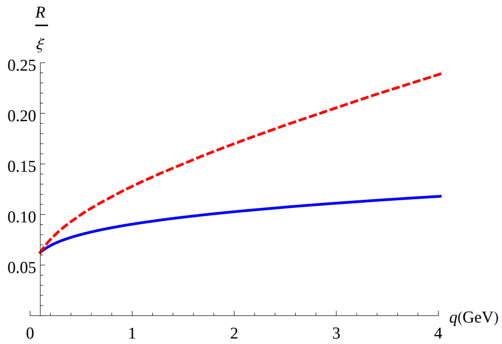

Figure 3: Running of R/ξ with q, assuming one (solid) and two (dashed) dark matter fermions. Here, $\alpha_d(q_0) = 0.25$, $q_0 = 0.1$ GeV, and $m_{Z_d} \lesssim q_0$ are assumed. A dark Higgs boson contributes to the running in both cases.

be significant and may result in loss of perturbative reliability for predictions. The running is more pronounced for light fermion states, but could still be significant for scalars for $\alpha_d \gtrsim 0.4$. These results suggest that one may be able to use the running effect, if measurable, to probe the number and the type (spin) of the low lying states in the dark sector.

An approach to measuring the running of $\alpha_d(q)$ may take advantage of the fact that at $q^2 > m_{Z_d}$ the scattering of DM from the nucleus is similar to electron or muon electromagnetic scattering from the nucleus governed by quantum electrodynamics. One may then normalize the DM scattering cross section $\sigma_{\rm DM}$ to the well-understood lepton scattering cross section $\sigma_{\rm EM} \propto 1/q^2$ which can be well-measured. We then have

$$R \equiv \sigma_{\rm DM}/\sigma_{\rm EM} \simeq \alpha_d\, \varepsilon^2/\alpha \simeq \xi\, \alpha_d^2\,, \tag{3}$$

with ξ approximately constant. In the above, we have used the typical assumption of loop-induced kinetic mixing that implies $\varepsilon^2(q) \propto \alpha_d(q)$. In Figure 3, we have plotted the running of R/ξ for one (solid) and two (dashed) light DM fermions and one dark Higgs boson, assuming $\alpha_d(q_0) = 0.25$, $q_0 = 0.1$ GeV, and $m_{Z_d} \lesssim q_0$. As can be seen, the running is significant for GeV $0.1 \lesssim q \lesssim 4$ GeV, typical of fixed target experiments, and the two cases are quite distinct, suggesting that with sufficient statistics one may uncover the low lying dark sector spectrum.

As α_d increases beyond $\mathcal{O}(1)$ values, the theory will become strongly coupled. However, in a sensible framework, this behavior should be terminated at some scale. A straightforward possibility is for $U(1)_d$ to transition to a non-Abelian gauge interaction that is asymptotically free. If this transition to new physics occurs at $q = q^*$, one expects $\varepsilon(q^*) = 0$, with a non-zero value induced below q^* due to the quantum effects of particles with masses $m < q^*$ that carry hypercharge and have $Q_d \neq 0$. However, such particles cannot be too light, $m \gtrsim 100$ GeV [10], given existing experimental bounds. Thus, on general grounds, we expect q^* to be larger than $\mathcal{O}(100\,\text{GeV})$.

For $\alpha_d(q^*)\ln(q^*/q_0) \gg 1$, we find

$$\alpha_d(q_0) \approx \frac{3\pi}{(2n_F + n_S/2)\ln(q^*/q_0)}\,, \tag{4}$$

where we have used a 1-loop approximation for the running. The above formula then yields the value of $\alpha_d(q_0)$ that would lead to the onset of a Landau pole at $q \sim q^*$. For example, setting

$q_0 = 0.1$ GeV and $q^* = 1$ TeV (a reasonable value given the preceding discussion), the upper bound $\alpha_d(q_0) \lesssim 0.5/(n_F + n_S/4)$ is obtained. Hence, for $m_{Z_d} \lesssim 0.1$ GeV, we may expect the upper bound $\alpha_d(m_{Z_d}) \lesssim 0.5$ as a generic guide for the invisible dark photon scenario, where dark states below m_{Z_d} are assumed.

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