Snowmass2021 - Letter of Interest

Low-mass Mediators of $U(1)_{T3R}$

Thematic Areas:

■ (TF08) BSM model building
■ (CF1) Dark Matter: Particle Like
■ (TF09) Astro-particle physics & cosmology

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Abstract: We propose that scenarios in which low-mass dark sector particles couple to a new gauge group ($U(1)_{T3R}$) under which some right-handed Standard Model fermions are also charged is an important topic of study at Snowmass.

1 Introduction

Scenarios in which right-handed fermions are charged under a new gauge group have been well-studied, originally in the context of left-right models (see, for example, [1–3]). Recent interest has focussed on scenarios in which first- and/or second-generation right-handed fermions are charged under $U(1)_{T3R}$, with up- and down-type fermions having opposite charge (similar to the subgroup generated by the diagonal generator of the $SU(2)_R$ of the original left-right models). Especially interesting is the case where the dark sector particles are low-mass (sub-GeV)[4].

The scenario is of interest for several reasons.

- This is a scenario where sub-GeV dark matter is a natural prediction[4].
- Although constraints on other examples of new $U(1)$ gauge groups (such as $B-L$, $L_i - L_j$, secluded $U(1)$, etc.) are well-studied, $U(1)_{T3R}$ presents unique features which arise from the coupling to chiral fermions[5,6].
- Despite its low mass, there are a variety of scenarios in which the correct dark matter relic density can be obtained through thermal freeze-out. Other mechanisms may also be possible.
- This scenario yields some interesting direct detection features. In particular, spin-independent velocity independent scattering mediated by the dark photon is naturally isospin-violating[7–9], and inelastic.
- Though there is open parameter space which is not exclude by an current experiments, a variety of upcoming experiments are poised to probe the open parameter space. This includes low-mass direct detection experiments (using a variety of techniques), fixed target/beam dump experiments, neutrino experiments, and colliders.
- Some scenarios can provide a high-scale solution to the H_0 tension[5].

2 Interesting Features of this Scenario

A sub-GeV dark sector. Since first- and/or second-generation right-handed fermions are charged under $U(1)_{T3R}$, this symmetry protects their masses. If the symmetry-breaking scale is relatively light ($\mathcal{O}(1-10)$), then the low-scale masses of first-/second-generation charged fermions would arise naturally, without excessively small Yukawa couplings. But this symmetry-breaking scale also feeds into the masses of the dark sector particles, implying that they are also naturally sub-GeV. These new sub-GeV particles include the dark photon, dark Higgs, right-handed neutrino, and potentially a pair of Majorana fermions (one or both of which can constitute the dark matter).

Qualitatively new constraints. There is a large literature discussing laboratory, astrophysical, and cosmological constraints on models with a light dark photon or dark Higgs[10–12]. But if the new gauge group is $U(1)_{T3R}$, then there are some qualitatively different constraints[6]. Because the dark photon couples to right-handed SM fermions, the longitudinal polarization does not decouple from tree-level processes. This produces an enhanced cross section for any process in which a hard dark photon from a tree-level process. As an example, we can consider the scenario where the muon is the only charged lepton coupling to the dark photon. This scenario is typically subject to much weaker constraints. But it has been shown that, if the Universe reheats to a sufficiently high temperature ($\gtrsim 0.1$), the coupling of the dark photon to right-handed muons would lead to enhanced production of the dark photon in the early Universe; constraints on ΔN_{eff}

thus rule out such scenarios for *arbitrarily small coupling* unless the symmetry-breaking scale is $> \mathcal{O}(10^6)$. Recent astrophysical constraints on ALPs coupling to muons in supernovae[13,14] can easily be repurposed as constraints on the longitudinal polarization of the dark photon (equivalently, the Goldstone mode), and these constraints are only slightly weaker.

The reach of future experiments. As a result of the enhanced production of the longitudinal polarization, these scenarios are much more tightly constrained. One cannot hide forever from experiments by going to weaker coupling. As a result, the region of parameter-space in which a sub-GeV dark sector is achieved naturally is finite, and will be probed by a variety of experiments which are either under construction or consideration. It is quite possible that future experiments will be able to discover or exclude this scenario in coming years. Colliders (FASER[15], Belle-II[16], Mathusla[17]), beam-dump/fixed-target experiments (LDMX[18], LDMX M^3[19], SHiP[20], SeaQuest[21], NA64μ[22]), neutrino experiments (COHERENT[23], CCM[24], DUNE[25]) can all play a role, and it is necessary to understand how they constrain scenarios with a coupling to chiral fermions.

Direct detection. Direct detection experiments can play an especially interesting role. Since the dark photon couples to up-type and down-type fermions with opposite charge, it leads to isospin-violating[7–9] spin-independent scattering. Moreover, since the dark matter candidate(s) are Majorana fermions, one necessarily has inelastic scattering. Indeed, scattering via a dark photon is necessarily inelastic if the dark matter is charged only under spontaneously-broken continuous symmetries; in that case, the dark matter is generically a real degree of freedom, which cannot couple through a diagonal vector current. A variety of new techniques for probing low-mass dark matter are being studied, but few with the inelastic or isospin-violating scattering in mind. Since this is a generic phenomenon, it would be good to study these prospects.

Relic density. Despite tight constraints on low-mass dark matter annihilation from Planck[26,27], there are regions of parameter space in which the dark matter candidate can have thermal relic density set by the freeze-out mechanism. Bounds from Planck can be evaded by p-wave annihilation, and by co-annihilation. But it worthwhile to determine if other mechanisms can be found for generating the correct relic density, which can expand the viable parameter space.

The H_0 tension. Moving away from scenarios in which the sub-GeV scale is generated naturally, one finds that scenarios with a very light dark photon but a very heavy symmetry-breaking scale ($> \mathcal{O}(10^6)$) can yield $\Delta N_{eff} \sim 0.2 - 0.5$[5], which can potentially play a role in resolving the H_0 tension. Such a symmetry-breaking scale is large enough to be inaccessible at current colliders, so it would be interesting to study other signatures of this scenario.

3 Conclusion

There is a unique phenomenology associated with the scenario in which some first-/second-generation right-handed SM fermions are charged under the new gauge group $U(1)_{T3R}$. In this case, a sub-GeV mass scale for SM fermions and dark sector particles can be naturally generated. There are tight constraints on the scenario, arising from production of the longitudinal dark photon polarization. As a result, there is a limited parameter space available in which this scenario provides a good dark matter candidate. But the available parameter space can potentially be explored by a variety of new experiments. Further study of this scenario will be a fruitful avenue at Snowmass.

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