Searching for Sub-Gev Dark Matter at Fixed Target Neutrino Experiments

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Abstract

Low mass dark matter theories, if produced as a thermal relic in the early universe, must be accompanied by light mediators in order to obtain the dark matter abundance observed in the present day universe. These light mediators in turn provide a channel for the production of dark matter at fixed target neutrino experiments, producing a relativistic dark matter beam, which could then be detected by neutral-current-like interactions in neutrino detectors. We consider the possibility that fixed target neutrino experiments such as MiniBooNE and T2K could serve as a new dark matter search avenue, sensitive to sub-GeV dark matter scenarios that would be otherwise undetectable. These experiments are found to provide sensitivity to light stable states that could serve as viable candidates for particle dark matter.

1. Introduction

Thermal relic dark matter possessing a mass below a few GeV is overproduced in the early universe unless some additional light states are introduced to mediate their interactions with the Standard Model. These hidden sector scenarios are perhaps the only means of introducing a viable sub-GeV thermal relic dark matter candidate. Constraining the parameter space of these scenarios is difficult, as by construction they escape many cosmological constraints, and they leave little in the way of signals detectable by direct and indirect dark matter searches. New strategies, using high-intensity experiments utilizing GeV electron and proton beams to study rare or weakly coupled states show great promise in allowing further exploration of this parameter space. We show the effectiveness of searches by Fixed Target Neutrino Experiments by studying a hidden $U(1)'$ scenario, mediated by a vector boson that kinetically mixes with the photon. As much of this work has been discussed in previous publications, we direct the reader to [1, 2] for details on the development of and reasoning behind the scenario, and to [3, 4] for more details on how the sensitivity of each experiment was calculated. This work will primarily be devoted to new developments since those papers, with a description of the existing constraints on the scenario in section 2 and some example sensitivity curves for two fixed target experiments, T2K and MiniBooNE, in section 3.
2. Scenario

We consider a hidden sector scenario charged under a $U(1)'$ symmetry, spontaneously broken by some Higgs' at a low energy scale and mediated by a vector boson $V$,

$$\mathcal{L} = \frac{1}{4} V_{\mu\nu}^2 - \frac{1}{2} m_V^2 V_{\mu}^2 + \kappa V_{\mu} \partial_{\mu} F_{\nu\rho} - |(\partial_{\mu} - e' V_{\mu}) \chi|^2 - m_\chi^2 |\chi|^2 + \mathcal{L}_H,$$

where $V_{\mu\nu}$ and $F_{\mu\nu}$ are the $U(1)'$ and electromagnetic field strengths, and $\kappa$ is the kinetic mixing strength between the $V$ and the photon. Note that while the $V$ does mix with the $Z$ boson, we will not consider the effect of this mixing as these interactions would be suppressed by the Z mass.

The scenario possesses four free parameters: $\kappa$, the coupling strength of the $U(1)'$ symmetry $\alpha' = e'^2/(4\pi)$, and the masses $m_V$ and $m_\chi$. We are primarily interested in dark matter masses $m_\chi$ between a few MeV and 1 GeV, as this region is not yet constrained by direct dark matter searches. We also require $m_V \geq 2m_\chi$ so that the invisible decay $V \to \chi \overline{\chi}$ is kinematically allowed, and dominates over the visible decays to Standard Model particles for sufficiently small values of $\kappa$. Finally, we have chosen to set $\alpha'$ equal to 0.1. Larger values are of course possible so long as the dark matter does not self-interact too strongly and the theory remains perturbative.

This scenario escapes many cosmological constraints due to the velocity suppression of the $p$-wave annihilation cross section, and is not yet subject to the increasingly sensitive limits placed by direct searches due to the low mass of the dark matter candidate. It is subject to limits placed by a number of experimental measurements relating to rare decays, missing energy searches and precision Standard Model measurements. In order to display the scenario parameter space and the regions already excluded, we show two 2-dimensional slices of the parameter space in figure 1. The left-hand plot is similar in many ways to the dark force or hidden/heavy photon constraint plots (see i.e [5]), and presents the parameter space in terms of $\kappa$ and $m_V$ for a constant $m_\chi$ and $\alpha'$. The right-hand plot is on the same axes as the direct detection sensitivity plots used by many experiments, and includes the best direct detection limits from a number of experiments. The direct detection plot is effectively in terms of $\kappa^2$ and $m_\chi$ for a fixed $m_V$ and $\alpha'$.

Visible decays of the $V$ provide some weak limits on the scenario parameter space, as $V$’s can be produced at even low energy experiments, and have very short lifetimes. While these searches provide a significant constraint on heavy photons, visible decays suppressed by a factor of $\alpha \kappa^2 / \alpha'$ in the hidden sector scenario, as the $V$ preferentially decays to invisible, hidden sector states. These limits are labeled $e^+e^-$ in figure 1.

Of greater concern is the $V$’s contribution to invisible decay widths and missing energy searches. Decays of the $\pi^0$ to a single photon and missing energy, and contributions to the invisible width of the $J/\psi$ are both included on the plot, with the later providing the best constraints on some portions of the low mass parameter space. Searches for $pp \to \text{jet} + \text{invisible}$ must also be considered, though current analyses do not rule out much of the parameter space. Far greater constraints come from monophoton searches by BaBar, which provide the best limits over much of the parameter space.

The hidden sector scenario makes extra contributions to many precision measurements of SM quantities through the introduction of additional diagrams involving the $V$. Shifts in the electron magnetic moment $g-2$ place some of the best constraints on the parameter space at the very low end of the $m_V$ range. Shifts in the muon magnetic moment are more complicated, as there is already great disagreement between theory and experiment. We have chosen to exclude parameter space that increases the disagreement between the theoretical prediction and experimental measurements to more than $5\sigma$. The $V$ could ameliorate the disagreement between theory and experiment, and the light blue band through the parameter space indicates the region of the parameter space where a better than $3\sigma$ agreement exists between theory and experiment. Virtual $V$ exchanges can also have a measurable effect on the $Z^0$ mass, and this has been labeled as “$\Delta m_Z$ and EW fit” in the constraint plots.

3. Sensitivity at Fixed Target Neutrino Experiments

Fixed Target Neutrino Experiments (FTNEs) provide an alternative probe of the hidden-sector parameter space. These experiments are capable of producing large numbers of relativistic hidden sector states
The sensitivity of the experiment was studied in previous works [2, 3], and we recast those results on the observation of 55 nonstandard NCE scattering events at a 90% confidence level at the LSND experiment here by excluding all of the parameter space for which LSND would expect to observe more than 110 dark matter candidates propagate through the neutrino detector where they could then be detected as excess neutral-current-like scattering events above those produced by scatterings of the neutrino beams. With their resulting in the creation of a “dark matter beam” alongside the observed neutrino beam. These hidden-sector dark matter candidates propagate through the neutrino detector where they could then be detected as excess neutral-current-like scattering events above those produced by scatterings of the neutrino beams. With their large data sets and low Standard Model backgrounds, FTNEs can achieve impressive sensitivity through a relatively straightforward counting experiment.

For $V$ masses below the mass of the $\pi^0$, the most significant constraints on this scenario are placed by the observation of 55 nonstandard NCE scattering events at a 90% confidence level at the LSND experiment [23]. The sensitivity of the experiment was studied in previous works [2, 3], and we recast those results here by excluding all of the parameter space for which LSND would expect to observe more than 110 dark matter scattering events, where we have chosen a weaker constraint to allow for up to a factor of two error in the $\pi^0$ production estimates. This curve is included as a constraint line in the sensitivity plots which follow. The beam energy at LSND is too low to produce any neutral mesons apart from the $\pi^0$ in large quantities, and so the experiment is incapable of probing larger $V$ masses.

A disadvantage of probing the hidden sector parameter space through counting experiments is that a substantial Standard Model background remains in the form of neutrinos. A possible strategy for the reduc-
The beam dump run was officially approved by the Fermilab PAC in January 2014.
4. Conclusion

Fixed target neutrino experiments provide large data sets with low Standard Model backgrounds, which allow for the undertaking of very sensitive searches for weakly-coupled sub- to few GeV new physics states. We examined a hidden-sector scenario that offers a viable sub-GeV thermal relic dark matter candidate with a parameter space that is largely unconstrained by standard dark matter search techniques and only weakly constrained by a number of particle physics searches for hidden photons. At low masses, fixed target neutrino experiments clearly provide the best limits on this parameter space with a straightforward counting experiment. Experiments with smaller data sets, but larger energies, are capable of providing significant limits on the parameter space by discriminating between hidden-sector and neutrino events using differences in the timing, angular and energy distributions of the particle species, or with greater effort, by reducing the number of neutrinos produced altogether. While impressive new constraints are being placed on the hidden-sector dark matter parameter space by analyses of FTNEs and electron colliders such as BaBar, a great deal of viable and interesting parameter space remains, which can only be explored by new experiments.

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