Hunting for light dark matter with DUNE PRISM

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Abstract. We present the prospects for exploring low-scale dark sectors with the future DUNE experiment and the impact of the movable off-axis near detector concept, DUNE-PRISM, and a higher energy beam configuration. We focus on a simple scenario which extends the Standard Model by a "dark" U(1), comprising scalar or fermion dark matter and a dark photon kinetically mixed with the photon. We consider nucleus and electron scattering signatures of dark matter produced in the beam via neutral pseudoscalar meson decays. Our results show that, by analysing the energy spectra of single electron events in multiple off-axis angle, DUNE-PRISM can substantially increase the experimental sensitivity to these models, reaching theoretical targets for thermal relic dark matter for a wide range of dark photon and dark matter masses.

1. Introduction

Although dark matter (DM) is undoubtedly present in our universe, its detection via non-gravitational effects has eluded us. One well-motivated hypothesis regarding DM is that, in the early universe, it was in thermal equilibrium with the standard model (SM) plasma before its interactions froze out, resulting in a relic abundance that persists today. One scenario that fits this description is that of a light dark sector where a DM particle (we assume it to be either a fermion χ or a complex scalar ϕ) interacts with the SM via a dark photon A' that mixes kinetically with the SM photon.

Recently, significant attention has been paid to the prospects of detecting sub-GeV DM in neutrino detectors, leveraged due to the accompanying intense proton beams for these experiments (e.g. [1, 2, 3, 4, 5, 6]). DM can be produced in the collision of protons on a target and travel to a near detector, interacting with nuclei or electrons. Of note is that these DM interactions look very similar to neutral current neutrino interactions. One way to reduce these backgrounds is to look off-axis, where the signal-to-background ratio of DM to neutrino events grows [4, 6].

In this talk, based on [7], we will discuss the possibility of the future Deep Underground Neutrino Experiment (DUNE) [8] to probe such a DM scenario. Specifically, we focus on the proposed DUNE-PRISM concept [9] in which the near detector moves up to ~ 36 m off-axis and on the tau optimised beam configuration (which we will refer to as high energy or HE configuration). We will show that the ability to perform measurements at different off-axis angles significantly enhances the sensitivity to light dark matter models.

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2. Light Dark Matter at DUNE

The strength of neutrino facilities searching for sub-GeV DM come from the production mechanism, in which protons strike a target, producing an abundance of charged and neutral mesons, which may decay to DM, which in turn travel to a detector producing a wide range of possible signals. We focus on a $U(1)_D$ dark photon scenario in which the dark photon mixes kinetically with the photon, and a new fermion χ or scalar ϕ is charged under $U(1)_D$. For fermionic DM, the Lagrangian of interest is

$$\mathcal{L} \supset -\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{M_{A'}^2}{2} A'_\mu A'^\mu + \overline{\chi} i \gamma^\mu \left(\partial_\mu - i g_D A'_\mu\right) \chi - M_\chi \overline{\chi}\chi, \tag{1}$$

where ε is the kinetic mixing between the SM and the new $U(1)_D$ (which has gauge coupling g_D), and $M_{A'}$ and M_χ are the dark photon and DM masses. We assume that the DM is a thermal relic and that its initial abundance is symmetric. In this case, the DM/A' masses and couplings will provide a target for which the relic abundance matches the observed abundance in the universe. We will show that DUNE-PRISM will be able to reach this target.

Dark Matter Production Assuming that the DM mass $M_{\rm DM}$ is lighter than half the mass of a pseudoscalar meson $\mathfrak{m}$ that is produced in the DUNE target, DM is produced via two decays, those of on-shell A' and those of off-shell A' (if $M_{A'} > m_{\mathfrak{m}}$ or $M_{A'} < 2M_{\rm DM}$). We use Pythia8 [10] to estimate the production of π^0 and η mesons and find that, on average, 4.5 π^0 and 0.5 η are produced per proton-on-target (POT). For any combination of $M_{\rm DM}$ and $M_{A'}$, we can estimate the differential DM flux that reaches the DUNE near detector as a function of energy, allowing us to estimate the experimental sensitivity to such a DM scenario.

Signals and Backgrounds at the DUNE Near Detector DUNE is designed primarily to study neutrino oscillations and cross sections, however the far (40 kt) and near (75 t) detectors will be powerful for searching for new physics. We assume that the near detector is located 574 m downstream of the production target, and is 3 m × 4 m × 5 m. For DM signals, we will assume that the DM scatters quasi-elastically off nucleons (DM + N → DM + N) and off electrons in the liquid argon (DM + e^- → DM + e^-). Neutrinos will produce events that look similar to this, either $\nu N \to \nu N$, $\nu_\mu e^- \to \nu_\mu e^-$ or the charged-current quasi-elastic (CCQE) scattering $\nu_e n \to e^- p$, in which the proton is not identified. For light DM/A', the cross section DM + e^- → DM + e^- can be significant, leading to one very forward-going electron (due to the boost of the system). In terms of the forward-going electron, the $\nu_\mu e^- \to \nu_\mu e^-$ background will be irreducible, however the CCQE background can be nearly completely vetoed. For details we refer to the full paper [7].

Advantages of searching on- and off-axis With a movable near detector (between 0 and 36 m transverse to the beam direction), the DUNE-PRISM concept will allow for precise measurements of the neutrino cross section [9, 11]. Additionally, the neutrino-to-DM flux ratio decreases as one goes off-axis, as neutrinos are produced via the decays of (focused) charged mesons, while the DM production we consider is due to decays of neutral mesons. Fig. 1 portrays this effect: we show the expected number of background (solid) and signal + background (dashed) events as a function of off-axis position, assuming one year of data collection. We show these curves for DM scattering off electrons both with (blue) and without (green) the CCQE background that we veto, and for scattering off nucleons (red). We see here that the signal-to-background ratio increases as $\Delta x_{\rm OA}$ increases, especially once the CCQE background is vetoed (green lines).

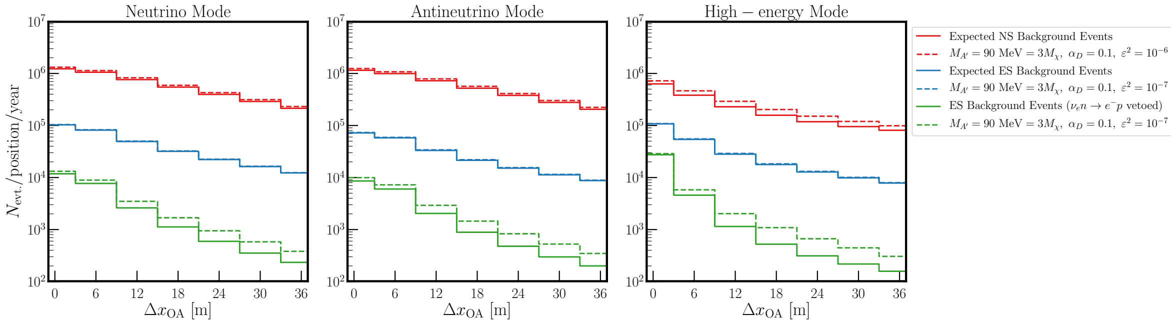

Figure 1. Expected number of events per year in neutrino mode (left), antineutrino mode (center) and HE configuration (right) as a function of detector off-axis distance. We show event rates for nucleon scattering in red, for electron scattering considering all backgrounds in blue, and with the CCQE background vetoed in green. We also display signal plus background events in dashed lines.

Statistical Tests: We assume that there is an overall flux-times-cross-section uncertainty $\sigma_A = 10\%$ correlated over all off-axis positions (but independent for all beam modes) and independent normalisation uncertainties $\sigma_{f_i} = 1\%$ at each off-axis position. These uncertainties are included in our test statistic as nuisance parameters with Gaussian priors, and then marginalised over in producing a resulting sensitivity reach. We also include measurements of electron recoil energy in our analysis. Because σ_A is significantly larger than σ_{f_i}, we expect that sensitivity will be far greater for an analysis that divides data collection across several off-axis positions than one that collects all its data on-axis. For both scattering channels, we will show DUNE sensitivity for three benchmark scenarios in order to compare. All three consist of an assumed 7 years total of data collection: **On-axis**, All data collected on-axis, 3.5 years of each neutrino and antineutrino modes; **DUNE-PRISM**, Data collected for equal time at each on/off-axis position: 3.5 years of each neutrino and antineutrino modes; **DUNE-PRISM-HE**, Data collected for equal time at each on/off-axis position: 3 years of nominal neutrino mode, 3 years of nominal antineutrino mode, and 1 year of high-energy configuration in neutrino mode only.

3. DUNE Sensitivity

We display expected DUNE sensitivities in Fig. 2, assuming $\alpha_D = 0.1$ and $M_{A'} = 3M_\chi$ (left) or $M_\chi = 20$ MeV (right). The resulting sensitivity for scalar DM ϕ is largely similar. We see that our estimates are significantly stronger than those from LSND and the MiniBooNE-DM search, as well as BaBar if $M_{A'} \lesssim 200$ MeV. We also show limits in the right panel from beam-dump experiments (we refer to the full paper [7] for a full list of references), as well as the lower limits obtained from matching the thermal relic abundance of χ with the observed one (black, dot-dashed) and from the Planck satellite (dashed orange).

4. Discussion & Conclusions

In this talk we have discussed the expected sensitivity of the future DUNE experiment to light dark matter models taking into account the synergies of the DUNE-PRISM detector and the high energy beam configuration. Two scenarios were considered for the estimate: fermionic and scalar dark matter below the GeV scale which interacts with the SM particles via a light dark photon kinetically mixed with the photon. We have found that, in both cases, the experimental sensitivity is substantially increased by the DUNE-PRISM ability to look at events off the beam

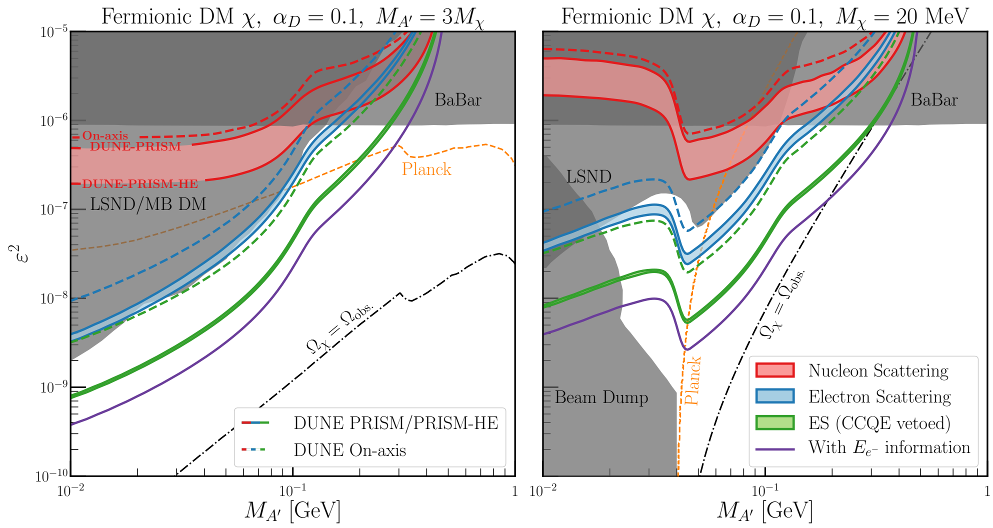

Figure 2. Expected DUNE sensitivities. We assume $\alpha_D = 0.1$ in both panels, and $M_{A'} = 3M_\chi$ ($M_\chi = 20$ MeV) in the left (right) panel. In red, blue and green we show the expected sensitivity using nuclear scatterings, electron scatterings, and electron scatterings with vetoed ν_e CCQE background. For each search, we show expected limits from **on-axis** (dashed), **DUNE-PRISM** (upper solid), and **DUNE-PRISM-HE** (lower solid) scenarios. Additionally, we show in purple the resulting expected limit when information on the recoiling electron energy, E_{e^-}, is included in the analysis.

axis. In this way, DUNE-PRISM will be competitive with dedicated experiments in probing light dark matter scenarios.

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