Snowmass2021 - Letter of Interest

Dark Sector Studies With Neutrino Beams

NF Topical Groups:

■ (NF03) BSM

RF Topical Groups:

■ (RF06) Dark Sector Studies at High Intensities

CF Topical Groups:

■ (CF01) Dark Matter: Particle Like
■ (CF03) Dark Matter: Cosmic Probes

TF Topical Groups:

■ (TF08) BSM Model Building
■ (TF09) Astro-Particle Physics & Cosmology
■ (TF11) Theory of Neutrino Physics

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Abstract: We highlight the exciting prospects for dark matter and dark-sector particle studies in accelerator-based neutrino experiments. These experiments, consisting generically of high intensity proton fixed target/beam dump facilities, can source large fluxes of dark sector particles in many well-motivated models. We characterize the types of searches that neutrino beam experiments can perform, and emphasize the advantages of using these experiments in tandem with dedicated dark-sector search experiments.

Introduction. The nature of dark matter (DM)[1] and the origin of neutrino masses[2] remain among the most pressing puzzles in particle physics. Both mysteries may suggest the presence of a *dark sector* comprised of Standard Model (SM) gauge singlet states that interact very weakly with the visible sector through a *portal* interaction. Neutrino experiments are by design ideally suited to study very weakly interacting particles, and this capability naturally extends to searches for DM and other dark sector particles (DSP). In this Letter we highlight the exciting prospects of current and planned accelerator-based neutrino experiments to explore the dark sector. In these experiments, as happens with neutrinos, copious fluxes of DM and DSP may be produced in the high-intensity proton fixed-target/beam dump collisions. These DSP can then be readily seen using short-baseline or near detectors downstream of the target. Due to the substantial intensity of the beams and the strong reconstruction capabilities of ongoing and upcoming detectors, accelerator-based neutrino experiments are poised to make great contributions to the search for beam-produced DM and DSP. These experiments will therefore play a critical and complementary role in the broader experimental quest to understand the DM and neutrino mass problems, as we highlight in the remainder of this letter.

Model	Production	Detection
Higgs Portal	K, B decay	Decay ($\ell^+\ell^-$)
Vector Portal	π^0, η Decay	Scattering (χe^-, χX, Dark Tridents)
	Proton Bremmstrahlung	Decay ($\ell^+\ell^-$, $\pi^+\pi^-$)
	Drell-Yan	Inelastic Decay ($\chi \to \chi' \ell^+\ell^-$)
Neutrino Portal	π, K, $D_{(s)}$, B decay	Decay (many final states)
ALP Portal (γ-coupling dominant)	Meson Decay	Decay ($\gamma\gamma$)
	Photon Fusion	Inverse Primakoff process
	Primakoff Process	
Dark Neutrinos	SM Neutrino	Upscattering + Decay ($\nu \to \nu_D$, $\nu_D \to \nu \ell^+\ell^-$)
Dipole Portal	Dalitz Decay	Decay ($\nu_D \to \nu\gamma$)
νphilic Mediators	SM Neutrino	Scattering (Missing $\not{p}_T$, SM Tridents)

Table 1: A selection of models that can be probed by neutrino beam experiments.

Models $\&$ **Signatures.** The phenomenology of a particular dark sector model are, to a large extent, governed by the structure of the dark sector, including the pattern of portal couplings to SM particles, as well as the number and mass ordering of dark sector states. A selection of popular dark sector models with their corresponding production/detection mechanisms at neutrino beam experiments is presented in Table 1. As highlighted there, the range of potential signatures is quite rich, and includes DSP decays to (semi-)visible final states and for DM/DSP scattering with SM particles[2–40]. These models can also be categorized based on the dominant DM/DSP production mode in the beam, as is shown in Table 1. Several models are testable using the SM experimental neutrino flux[41;42]. Neutrino trident signals can be a sensitive probe of new, light neutrinophilic mediators[43–47], as can missing-transverse-momentum searches in neutrino scattering events, where the neutrino emits an on-shell, invisible mediator[48;49]. Additionally, so-called "dark neutrino" or "dipole-portal heavy neutral lepton" models[21;26–29;50–52], where the SM neutrinos up-scatter into a new, unstable state in or near a detector, rely on the SM neutrino flux for searches in neutrino experiments.

Advantages of Neutrino Experiments. As emphasized above, dark sectors give rise to a rich variety of phenomena, leading to striking signatures in a variety of dedicated and multi-purpose terrestrial experiments and/or astrophysical observatories[1;2;53;54]. Accelerator-based neutrino experiments provide a complementary and, in many scenarios, unique probe of DM/DSP. For instance, neutrino beam probes are insensitive to assumptions about the ambient population of DM or the astrophysical flux of DSP. Furthermore, in contrast to direct detection experiments, where DM scattering occurs at non-relativistic velocities, the relativistic beam-produced DM/DSP signals are relatively insensitive to the specific Lorentz structure of the interactions. In comparison to other terrestrial probes, neutrino beam experiments offer several significant advantages. These include the enormous collision luminosities inherent in high-intensity proton fixed target experiments, as well as the excellent particle identification and reconstruction capabilities of modern neutrino detectors that help to distinguish DSP signals from beam-related and cosmic backgrounds. Timing measurements offer another important experimental handle along with the energy measurement to distinguish the DM/DSP relative to SM neutrinos[55–58]. For certain signatures with irreducible SM neutrino backgrounds (e.g., DM scattering), even greater sensitivity is possible if neutrino experiments are run in a beam-dump mode, in which the proton beam is dumped directly at the absorber. On the other hand, many motivated DM/DSP searches are most effectively carried out in neutrino or anti-neutrino run mode, particularly those in which the SM neutrino flux, or a new particle flux from light, charged mesons, is relevant. With this strong physics case, it is also worth noting that many new experiments are planned, funded, built, and operating over the next decade. The opportunities presented here therefore do not demand an excessive amount of new resources.

The Experimental Landscape. Many previous or currently-operating neutrino experiments have demonstrated sensitivity to DM and DSP models of the type in Table 1. Among these are CHARM[59–61], NuCal[35;62;63], MINOS, MiniBooNE[5;8;16;23;26–28;64] (and its dedicated DM search[55;65;66]), MINERvA[29], ArgoNeuT[67;68], T2K[69], MicroBooNE[56;70], and JSNS^2[24;58]. Experiments studying CEνNS can also provide powerful DSP probes, including the accelerator-based experiments such as COHERENT[11;30;57;58;71] and CCM[58;72], as well as reactor-based experiments like MINER, CONUS, and CONNIE[73]. In the near future, the Fermilab SBN program will begin to explore these models with the SBND, MicroBooNE (already operating), and ICARUS experiments[74–76]. Finally, in the coming decade, DUNE will improve on these searches with its rich near detector complex[15;23;36;49;67;77–79].

Tools. New tools are being developed to study DM and DSP models in a robust way at these experiments. This includes improved calculation and simulation of production and scattering as relevant. On the production side, dedicated codes like BdNMC[16] and MadDump[80] allow for robust simulation of a variety of DM and DSP production scenarios. An alternative approach relevant for production via meson decay is to use tweaked output from Geant4[81] beam simulation codes[75]. Combining these tools provides a new level of accuracy in simulating production. Scattering can be complicated to simulate in cases where DM scatters by interacting with nuclear matter. Dedicated neutrino Monte Carlo codes such as GENIE[82;83] contain detailed nuclear models to account for elastic and inelastic scattering, nuclear structure, and final state interactions of particles escaping a struck nucleus. A new tool[84] has been developed to use GENIE to generate DM scattering events. In addition to allowing for more robust simulation of scattering processes over a range of energies, this tool, being based on GENIE, can more easily be plugged into simulation chains used by neutrino experiments. These tools remain under active development, with new features and models being added. In the coming years, new phenomenological studies making use of them will serve to enhance the physics case for the searches we discussed above and allow for robust results that can have improved sensitivity.

Outlook. Neutrino experiments, both those currently operating and those slated to begin soon, will play a crucial complementary role in probing a wide range of DM/DSP models. In preparation for this wealth of data, it is important to further study the capabilities of neutrino experiments to probe these models, as well as to develop appropriate triggers to ensure that these models are not missed. Further development on the Monte Carlo tools will help obtain increasingly accurate predictions for the signals and allow for the development of more sensitive analyses. In the case of liquid argon time-projection chamber detectors such as those of the SBN program, the reconstruction capabilities and algorithms are still under development. Developing a robust analysis program at SBN will further help future searches at the DUNE ND complex. Given the rich set of opportunities outlined in this Letter, DM/DSP searches offer an essential expansion to the physics program of neutrino experiments.

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