Snowmass2021 - Letter of Interest

Concept for a Neutral-Rich Three-Dimensional Sign-Selecting Focusing System

AF Topical Groups:
■ (AF1) Dark matter: particle-like
■ (AF5) Dark energy and cosmic acceleration: cosmic dawn and before

NF Topical Groups:
■ (NF3) Beyond the Standard Model

RF Topical Groups:
■ (RF6) Dark Sector Studies at High Intensities

Contact Information:
Jaehoon Yu (University of Texas at Arlington) [jaehoonyu@uta.edu]

Authors: Brian Batell (University of Pittsburgh), Vedran Brdar (MPIK Heidelberg), Albert De Roeck (CERN), Milind Diwan (Brookhaven National Laboratory), Bhaskar Dutta (Texas A&M University), Wooyoung Jang (University of Texas at Arlington), Doojin Kim (Texas A&M University), Seodong Shin (Jeonbuk National University), Alexandre Sousa (University of Cincinnati), Zahra Tabrizi (Virginia Tech) and Jaehoon Yu (University of Texas at Arlington)
Endorsers: Animesh Chatterjee ((University of Pittsburgh), Jong-Chul Park (Chungnam National University), Ian Shoemaker (Virginia Tech) and Adrian Tompson (Texas A&M University)

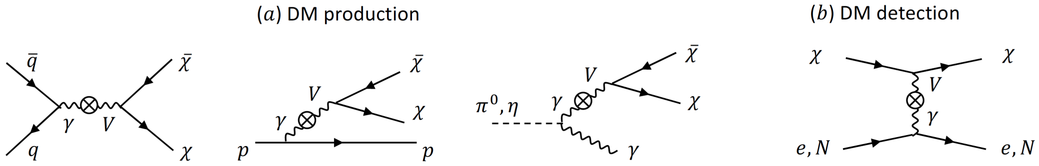
Abstract: The powerful future neutrino experiment facilities enable searches for Beyond the Standard Model phenomena in these experiments. Of these, low-mass dark matter and other charge neutral particles could also be produced in the neutrino target and the beam dump. This Letter of Interest discusses an idea of utilizing a three-dimensional sign-selected focusing horn train system that would permit the co-existence of beam-dump style experiments and the precision neutrino experiments. The key component in this system would be a three dimensional dipole that would direct horn focused charged particle beams toward the direction of the neutrino experiments with minimal loss. This paper discusses concept of such system that can enhance signal to background ratio by several orders of magnitude and some considerations that must be incorporated in such system which could eventually be used for key component of a dark matter beam facility if the dark matter is discovered in these facilities.

Introduction: Dark matter is a compelling observational motivation for physics beyond the Standard Model (SM). Over the past several decades, an enormous number of experiments have been made for detection of dark matter through its hypothetical non-gravitational interactions with ordinary matter, for example, dark matter direct/indirect detection and accelerator-based experiments, mostly focusing on the weakly interacting massive particles. However, the null observation of conclusive signals offers an opportunity to contemplate alternative ideas and methods for searching for dark matter signals, potentially extending by a significant amount of the phase space for discovery.

Precision physics at the next generation neutrino experiments requires high-intensity neutrino beams and large-mass detectors. These requirements necessitate high-power proton beams and high-capability near detectors to minimize both the statistical and systematic uncertainties as well as large mass far detectors. These advanced facilities provide enormous opportunities to explore Beyond the Standard Model (BSM) physics[1].

Low-mass Dark Matter and other Neutral particle searches The potential for discoveries at future neutrino experiments is enormous. Some of the rare particles that can be produced and discovered with high-intensity proton beams are low-mass dark matter χ (LDM), dark photons, heavy neutral bosons and leptons, and axion-like particles (ALP). For example, as shown in Fig. 1(a), LDM can be produced in the neutrino target or in the beam dump by the decay of dark photons produced through Drell-Yan, bremsstrahlung, cascade photons, and meson decays in combination with the kinetic mixing with the SM photon[2;2–6]. χ then (up-)scatters off an electron or a nucleon, as shown in Fig. 1(b). For example, recent MiniBooNE [7;8] results are from similar beam-dump LDM appearance searches. For another example, ALPs can be produced in the target via Primakoff scattering and undergo inverse Primakoff scattering resulting in a photon or decay-in-flight to a photon pair inside the detector[9]. All these final states induced by such new particles, however, are very similar to neutrino interactions via both CC and NC interactions, and thus the SM neutrinos are the primary background to the signals of interest. It is shown recently the SM background can be removed by utilizing the timing and energy distributions in the CEνNS experiments (e.g., COHERENT)[4] where a large region of LDM parameter space can be investigated. In this Letter of Interest, we propose to remove the SM ν background at the neutrino experiments with a higher energy beam (e.g., DUNE).

Neutrino Beam Production Mechanism: Neutrinos in the experiments are produced through the decay-in-flight of charged mesons resulting from the high-energy proton beams inciding on the primary target. In order to cover a wide range of neutrino energy for precision CP phase (δ_{CP}) measurement in neutrino oscillation, a string of three-dimensional focusing horn magnets are used to direct toward the neutrino detectors as many charged mesons (mainly $\pi^{\pm}$) as possible, with a range of momenta also as wide as possible. These focused charged mesons then travel through a long decay pipe (evacuated or filled with helium) allowing them to decay in flight with minimal scattering. The remaining un-interacted beam protons, surviving charged mesons, and unwanted decay products (e.g., $\mu^{\pm}$) are then absorbed in the beam dump while the produced neutrinos continue to travel toward the neutrino detector system.


(a) DM production

(b) DM detection

(c) Sign-selected 3D horn focusing system

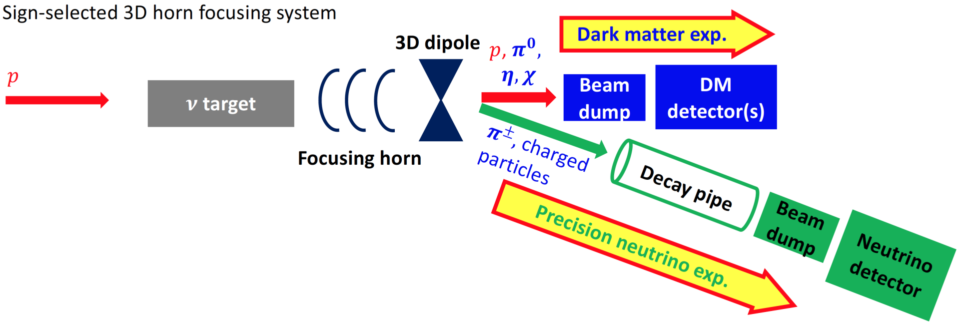


Figure 1: (a) (Fermionic) LDM production mechanisms in the neutrino target: Drell-Yan, bremsstrahlung, and meson decays. (b) LDM detection diagrams in the detector through the elastic scattering with an electron or nucleon. (c) A cartoon diagram of the sign-selected three-dimensional horn focusing system that would permit the co-existence of the precision neutrino experiment and beam-dump type LDM or other rare neutral particle searches.

Neutrino Beam Sign Selection System Taking advantage of the fact that neutrinos are produced from the decays of charged mesons, while rare particles such as LDM and ALP produced in the target are charge neutral, it is possible to separate these neutral particles from neutrinos by giving a magnetic "kick" to the focused secondary charged beams as schematically depicted in Fig. 1(c). The concept of providing a magnetic kick for a sign-selected neutrino beam was implemented by the NuTeV (E815) experiment to reduce systematic uncertainties on precision weak mixing-angle measurements. In the sign-selected quadrupole train (SSQT)[10;11], the 900 GeV proton beam from the Tevatron is sent to the neutrino target at a slight upward incident angle with respect to the axis to the detector. A dipole is positioned immediate downstream of the target to select the secondary charged particles of the desired sign by bending them to the beam axis pointed to the detector. These selected secondary charged particles are then sent through a train of quadrupole magnets to focus them. The wrong-sign secondary charged particles are bent away from the proton incident axis at the same angle as the right-sign particles, but in the opposite direction, thus reducing the contamination from the wrong-sign-associated neutrinos. The remaining un-interacted beam protons and neutral mesons such as π^0 and η^0, as well as neutral Kaons which represent additional sources of systematic uncertainties due to their ν_e final states, continue to fly along the incident proton beam axis into the dump away from the detector axis. The present and future neutrino experiments use focusing horn systems to sign-select and maximize the secondary charged particle flux, similar to the SSQT but with much higher efficiency and in three dimension.

Enriching Neutral Component of the Beam: Borrowing from the concept of SSQT, we propose to develop magnet train system to enable the co-existence of the precision neutrino experiments and beam-dump style neutral particle search experiments. Figure 1(c) shows a cartoon for such a system. High-intensity proton beams are sent to the target. The secondary particles are then sign-selected and focused through the optimized horn system. A three-dimensional dipole is placed immediately downstream of the horn string to take the cylindrical focused secondary charged particles and bend them with minimal loss toward the direction of the neutrino experiment facility consisting of decay pipe, dump area, and finally detector complex(es).

The remaining un-interacted high-energy beam protons and charge neutral particles, traveling in the same direction as the incident primary protons, proceed toward a beam dump. A high-precision detector to enable discovery of these new particles can then be placed behind the dump as close as possible to reduce the loss of the flux. Given that these particles have very small cross section with SM particles, an array of multiple experiments can be placed in the dark matter experiment facility (DMEF). Since most of the charged particles are bent away before they decay to neutrinos, the beams in the DMEF would be enriched with these neutral particles, with a greatly reduced background neutrino component, except for low-energy neutrinos resulting from pion decays upstream of the 3D dipole. A back-of-the-envelop calculation shows that a 5 orders of magnitude reduction of the neutrino flux directed towards the DMEF is possible, under the assumption of 100% bending efficiency. In addition, since the dump and the detector on DMEF could be placed immediate downstream of the dipole while the neutrino facility would require a long decay region followed by the dump and additional range out system, an additional gain of the neutral particle flux by two orders of magnitude is possible. These results in signal to background ratio enhancement of four to five orders of magnitude, a substantial and worthwhile gain.

Considerations: The scenario discussed above is very conceptual. In reality, there are several challenges that must be dealt with. First and foremost, the dipole that plays the key role in this system must be able to take the horn-focused cylindrical beam with the secondary charged particle momentum varying in the radial direction from high in the center to low momentum in the perimeter. The dipole must maintain the shape of the cylindrical beam with a minimal loss of the charged particles since any loss in the dipole will directly impact the neutrino flux and will irradiate the dipole and other beam line components. A dipole magnet fulfilling these requirements does not exist at present, so the technical challenges associated with creating the 3D dipole field need to be addressed.

In addition, the location of the dipole and the total length of the horn focusing and dipole system are important. They potentially impact the low-energy neutrino flux, since the low-energy charged mesons will predominantly decay in the target and throughout the length of this system before the bend. As wide-band neutrino beams are needed for precision δ_{CP} measurements, a careful design of this magnet system is crucial. There are other practical considerations that must be given, such as radiation hardness of the dipole and radiation effect from the losses.

Conclusion and outlook: In this Letter of Interest, we discussed a novel conceptual magnet system that could permit the co-existence of precision neutrino experiments and beam-dump style discovery experiments, reducing the neutrino background by several orders of magnitude. Based on a rough estimate, a gain in signal to background ratio of four to five orders of magnitude is possible. If neutral particles including dark matter are discovered in such facilities, this concept could also serve as a key component to create beams of these particles. The successful realization of this concept hinges on overcoming the technical challenge of designing the 3D dipole magnet. However, given the substantial gain in signal to background ratio, this idea presents a worthwhile novel idea for a potential new source of revolutionary discoveries.

References

[1] C. Argüelles et al., *White Paper on New Opportunities at the Next-Generation Neutrino Experiments (Part 1: BSM Neutrino Physics and Dark Matter)*, `1907.08311`.

[2] B. Batell, M. Pospelov and A. Ritz, *Exploring Portals to a Hidden Sector Through Fixed Targets*, *Phys. Rev. D* **80** (2009) 095024, [`0906.5614`].

[3] P. deNiverville, M. Pospelov and A. Ritz, *Observing a light dark matter beam with neutrino experiments*, *Phys. Rev. D* **84** (2011) 075020, [`1107.4580`].

[4] B. Dutta, D. Kim, S. Liao, J.-C. Park, S. Shin and L. E. Strigari, *Dark matter signals from timing spectra at neutrino experiments*, *Phys. Rev. Lett.* **124** (2020) 121802, [`1906.10745`].

[5] L. Buonocore, C. Frugiuele and P. deNiverville, *Hunt for sub-GeV dark matter at neutrino facilities: A survey of past and present experiments*, *Phys. Rev. D* **102** (2020) 035006, [`1912.09346`].

[6] B. Dutta, D. Kim, S. Liao, J.-C. Park, S. Shin, L. E. Strigari et al., *Searching for Dark Matter Signals in Timing Spectra at Neutrino Experiments*, `2006.09386`.

[7] MiniBooNE collaboration, A. Aguilar-Arevalo et al., *Dark Matter Search in a Proton Beam Dump with MiniBooNE*, *Phys. Rev. Lett.* **118** (2017) 221803, [`1702.02688`].

[8] MiniBooNE DM collaboration, A. Aguilar-Arevalo et al., *Dark Matter Search in Nucleon, Pion, and Electron Channels from a Proton Beam Dump with MiniBooNE*, *Phys. Rev. D* **98** (2018) 112004, [`1807.06137`].

[9] J. B. Dent, B. Dutta, D. Kim, S. Liao, R. Mahapatra, K. Sinha et al., *New Directions for Axion Searches via Scattering at Reactor Neutrino Experiments*, *Phys. Rev. Lett.* **124** (2020) 211804, [`1912.05733`].

[10] NuTeV collaboration, J. Yu, *NuTeV SSQT performance*, *Fermilab-TM-2040* (1998) .

[11] NuTeV collaboration, R. Bernstein, *Sign-Selected Quadrupole Train*, *Fermilab-TM-1884* (1994) .