Search for Hidden Sector and Dark Matter Particles produced at Fermilab's NuMI Target.

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In the long tradition of exotic searches at fixed-target experiments, we plan to use the NuMI beam-target and the NOvA Near Detector to observe potential signatures of Hidden Sector or Dark Matter particles, either directly produced within the target or through theoretically postulated mediators. Expecting mostly scattering events on electrons or nucleons as their signatures, an example of a mediator generated scalar dark matter particles is used to discuss the target production profile of a dark matter beam. This channel explores the capabilities of the detector to observe neutral-current events from electron-neutrino scattering interactions.

1 Introduction

Worldwide, the search for New Physics particles is getting more intense. Global broken symmetries may give rise to the elusive Axion (meV) and other Axion-like-particles (ALPs) which do not bind their masses with the weak scale coupling. Particles from these *Hidden* or *Dark Sectors* (HS) are not charged under the Standard Model and they are generically referred to as *Dark Matter candidates* (DM). A brand new particle discovery will be overwhelming proof of the existence of the postulated New Sectors in nature. It will not only define the High Energy Physics research in this century, but will also give us either the first dynamic coupling, (in the case of Axions), or a view into nature's intentions, (in the case of HS), where there are no reasons to have any anthropic motivated fine tuning of parameters.

The lowest dimension operator through which HS couple to the Standard Model is called a *portal*. Several models exist such as *Vector Portal, Heavy Neutrinos Portal, Axion Portal*, and others that may explain a very weak coupling of these sectors to the standard model. Search ideas born from these portals appear in a community-wide study in [1]. Several model independent plans in this literature utilize the proximity of neutrino near detectors to intense fixed-target setups that drive accelerator-based neutrino measurements. In this work, and in [2], we estimate an example of the DM flux to a near detector. We use the Vector portal to simulate the production of a vector mediator V_χ that decays into a pair of scalar DM particles $(\chi, \chi^\dagger)$.

2 NuMI and NOνA

Currently, the most intense neutrino source is the NuMI (Neutrinos at the Main Injector) ν_μ beam. It is a fixed-target system at the end of the Main Injector (MI) accelerator complex at Fermi National Accelerator Laboratory. Neutrinos are the tertiary beam coming out of the target complex used to feed the MINOS and MINERνA experiments with a baseline power of 320 kW.

For the needs of the new flagship experiment of Fermilab called NOνA (NuMI Off-axis electron-neutrino Appearance), MI has been upgraded to 500 kW. It delivers multiple proton groups (bunches) stored in each burst (spill) of 10 μsec (Fig. 1) every 1.67 sec. Since September of 2013, it has delivered almost 3.25×10^{20} protons on the target (POT). Further upgrades to the Booster accelerator that feeds MI are expected to bring the intensity to 700 kW within a year. The projected integral beam is 5×10^{21} POT within the 6 years of the NOνA run plan. This is more intense than the most severe constraints for the production of dark matter particles in the literature (see [2]).

The main function of the NOνA Near Detector (ND) [3] is to measure, near the source, the energy spectrum and profile of the ν_μ beam and the ν_e background expectation within the range of 1-3 GeV. Its segmented design of $4cm \times 6cm$ cells and its construction of low-Z plastic material gives it an estimated energy loss of about 10 MeV/cell or $0.18X_o$/plane. This makes it very competitive for detecting electron tracks for a wide range of energies 0.1-60 GeV as shown in the study in [2].

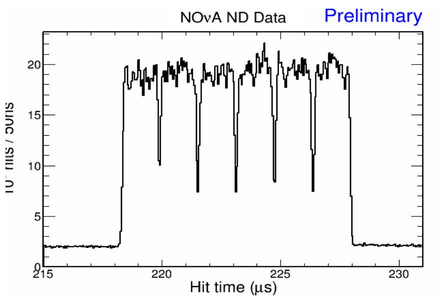

Figure 1: The NOνA timing peak (all hits) seen at the Near Detector. The full *spill* is shown arriving to the detector after the hardware imposed delay of 218 μsec and the beam structure is from the individual *bunches* of 18.8 ns each.

3 Dark matter production and flux simulation

The MI proton beam with 120 GeV on the NuMI carbon fixed target provides all of the available energy of 15 GeV for the mass of a directly produced vector mediator particle. Therefore, the sensitivity of the ND to DM extends up to 7.5 GeV. In this work, we present one example of a calculation of DM flux into the NOνA ND. We use a model of scalar DM production ($\chi, \chi^\dagger$) for three mass cases m_χ=100, 300, and 450 MeV through the Vector Portal by the direct creation of a vector mediator particle (V_χ) of mass 1 GeV. The interaction $p + p \to V_\chi \to \chi + \chi^\dagger$ from [5] is the input to PYTHIA 8 calculation framework [6] producing the angular and energy distributions of the dark matter flux profile in Fig. 2. We chose this example so we can compare the product distributions to a similar analytical estimation by deNiverville *et al.* in [5]. As the ND is off axis and its angular acceptance is $0.6^o - 0.8^o$ [2], we compare the 300 MeV case distribution to the same one from [5] for the forward lab-angles less than 2^o ignoring the dependence on angles away from the direction of the initial proton beam direction (Fig. 2, left). This gives us a handle for the size of production rate of DM as is estimated in [5] from various astrophysical and cosmological constraints. The energy spectrum of χ in Figure 2 right comes from events that have an angle to the beam in the lab frame within the ND acceptance range. The distributions are normalized to the total events in the 300 MeV case. The two distributions of Figure 2 make the DM beam profile.

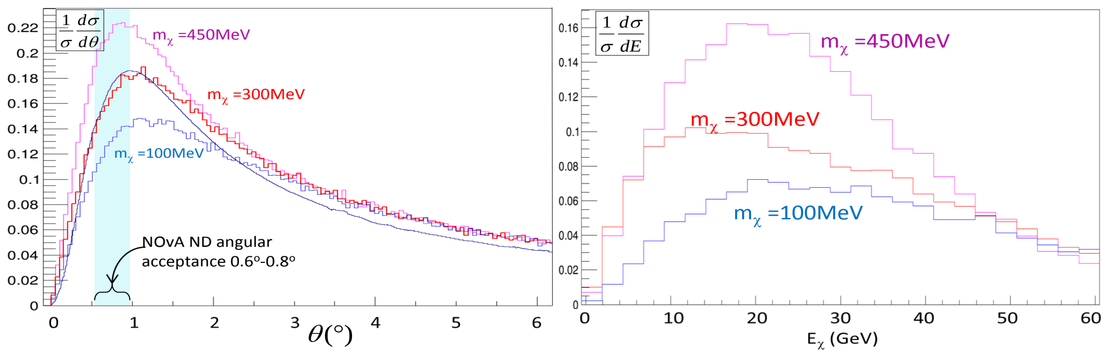

Figure 2: (left) The angular distributions of the χ's in the lab frame. The distributions are labeled by the m_χ. The 300 MeV curve is compared to the smooth curve taken from [5] and fits well for $\theta < 2^o$ within only a normalization factor. (right) The energy spectrum of the χ's that cross into the NOνA ND is normalized to the number of events from the 300 MeV curve.

4 Discussion

Figure 2 (right) shows that the energy spectrum of the dark matter extends from few to 60 GeV, peaking at around 20 GeV. This covers the complete range of the detector response to high energy signatures as seen in [2]. The large DM masses from NuMI and the ns resolution expected from the NOνA system may also allow us to use time-of-flight techniques in the DM signature reconstruction. That can keep the detection efficiency [2] be around 10^{-3}, depending only on detector acceptance and software reconstruction capabilities. Of course, in order to make a model independent measurement, the analysis of the data will proceed in the backward direction. That is, identifying any regions of excess events and attempting to interpret them from their kinematics (energy transfer to the scattered particle, direction of the scattered product, time of flight with respect to the prompt neutrino beam coincident with the accelerator cycle, etc.) and then, attempt to compare which are the most probable models predicting such distributions.

Future experiments, like LBNE [7] (expected to start in 2022), with an on-axis detector can potentially have improved time resolution, efficiency and finer granularity in the tracks but also they must compensate for the neutrino background that will be over the full energy range of signals in the near detector. In the meantime, NOνA will have the advantage of having the neutrino background energy spectrum peeled back below 5 GeV. This may allow us to see several events in excess to the predicted neutral current spectrum, and so probing models of DM production in the order of a pico-barn of cross section for each detected event during the 6-year of the NOνA run plan.

5 Conclusions

The weak coupling of the Hidden/Dark Sectors to Standard Model make fixed target neutrino experiments sensitive to dark matter mass below 10 GeV. In anticipation to the first NOνA production runs, at the world's most intense fixed-target beam during the fall and winter of 2014 with the newly commissioned Near Detector, we have presented an example of our expectations of the source and the kinematics of the dark matter particles that could be seen in the NOνA near detector. The debate on the sensitivity is critically dependent on the model that each favors but we expect a model agnostic attidude can help find the answers within the data.

6 Acknowledgments

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