Light Dark Matter in the NOνA Near Detector: First Look at the New Data

Athanasios Hatzikoutelis

University of Tennessee Knoxville, Knoxville, TN, USA

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The neutrino oscillations experiment NOνA is the flagship of Fermi National Laboratory. The neutrino source NuMI is delivering record numbers of protons-on-target surpassing the most stringent dark matter production upper limits of current models in the under-10 GeV mass range. We take advantage of the sophisticated particle identification algorithms of the experiment to interrogate the data from the 300-ton, off-axis, low-Z, Near Detector of NOvA during the first physics runs. We search for signatures of sub-GeV or Light Dark Matter (LDM), Axion-like-particles, and Heavy or Sterile Neutrinos that may scatter or decay in the volume of the detector.

1 Introduction

The NOνA (NuMI Off-axis electron-neutrino Appearance) [1] is the biggest particle physics experiment in the US currently and is hosted by Fermi National Accelerator Laboratory (Fermilab) and U. of Minnesota. It uses the most intense neutrino source in the world called NuMI (Neutrinos at the Main Injector). The ν_μ beam is produced by the 120 GeV protons of the Main Injector (MI) accelerator interacting in a carbon target at the NuMI target complex. Neutrinos are the tertiary beam coming out of this source that feeds the MINOS+ and MINERνA experiments as well.

The LDM title has been covering several types of New Physics candidate particles from Axion-like-particles that come from global broken symmetries, to Hidden Sectors interpreting SUSY models [2], all the way to some types of Heavy or Sterile Neutrino (Heavy Neutral Leptons -HNL) that come from the minimal extensions of SM [3]. They are not charged under SM and do not bind their mass with the Weak-scale couplings. The lowest dimension operators (*Portals*) that may couple both to SM and the lightest of the members of these structured *Sectors* may explain a very weak coupling of these particles to SM.

2 The NuMI-NOνA as a beam-dump experiment

The main function of the NOνA Near Detector (ND) [1] 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 (Figure 1). Its segmented design of 4 cm×6 cm 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 a study in [4].

Re-interpreting the NOνA ND as a beam-dump experiment opens the door to searches of rare events without any bias towards a particular model. The MI machine that feeds the NuMI source has been recently upgraded to 500 kW. It delivers multiple proton groups (bunches) stored in each burst (spill) of 10 μsec every 1.67 sec. Since September of 2013, it has delivered almost 3.25×10^{20} protons on the target (POT). About 1 km of earth is separating the NuMI-target from the 300-ton ND protecting it from any kind of products from the interactions at the target, besides the neutrinos and whatever other weakly-interacting LDM particles that may be produced.

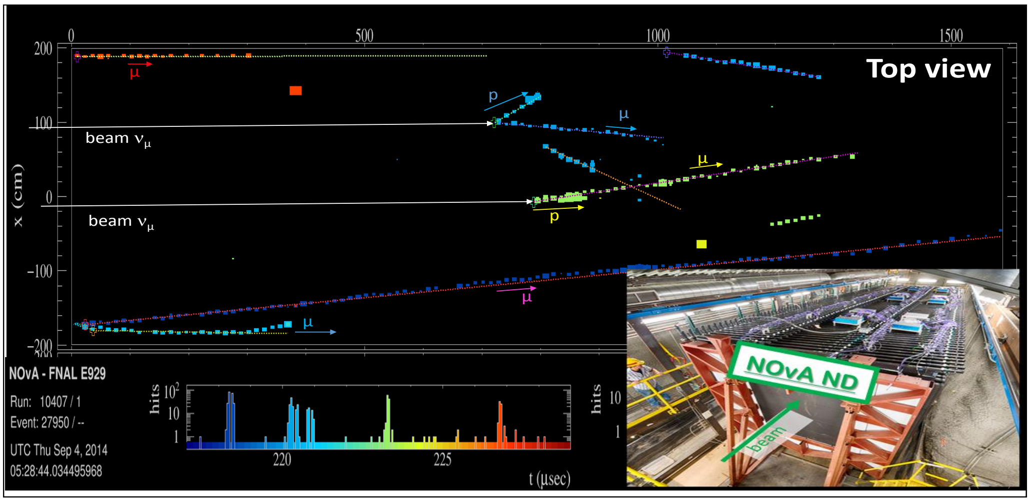

Figure 1: Event display of NOνA ND with a typical event (Top view) at 350 kW. (insert) The NOνA ND in its cavern at 11 meters from the beam center at left along the beam. It is usual to have events with five, identified, neutrino induced, interactions on nuclear targets in the detector and the surrounding walls of the cave (*rock muons*). The signatures from particles that are associated with neutrino interactions are highlighted (color denotes groupings in time) and labelled with two of the incident neutrinos artificially imposed on the display.

3 First look at the data

Even though we make every effort to use minimal assumptions and no model bias, we need to use a simple LDM model for illustration purposes. We choose here, a well-studied model [5] that assumes the Vector Portal model with a GeV-mass vector mediator which decays into a pair of scalar, MeV-mass, DM particles [4] that, in turn, fly to the ND where they may scatter elastically on atomic electrons. These events leave signatures of single, energetic, electron-induced, showers that are identical to the Neutral Current (NC) type of ν-induced interactions (the illustration in the insert of Figure 2 left). The NC events are the background to this LDM model signatures.

For this first look at the data we use the NOνA official preselection rules designed to identify

NC events. They have proven quite successful in identifying NC events in the primary energy range of (1–3) GeV that is the focus of the NOνA measurement [6]. We apply these rules to data from events covering the full energy range where events appear. For the small sample we are using in this work, the range extends up to little over 20 GeV. We search for spectral distortions (excess events) between the predicted distributions of the neutrino interactions that have no LDM channel included in the simulation (MC) and the data that may contain extra channels possibly from LDM. 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.

For the size of the current sample used, and for pico-barn cross-section for scattering on atomic electrons, one would expect, for the range of (5–25) GeV, about $O(10)$ excess events to the simulated, pure neutrino, spectrum. In the right plot of Figure 2, we show the shape difference between the data spectrum and the simulated (MC) one. For all three studied energy bands, the average is consistent with no excess events.

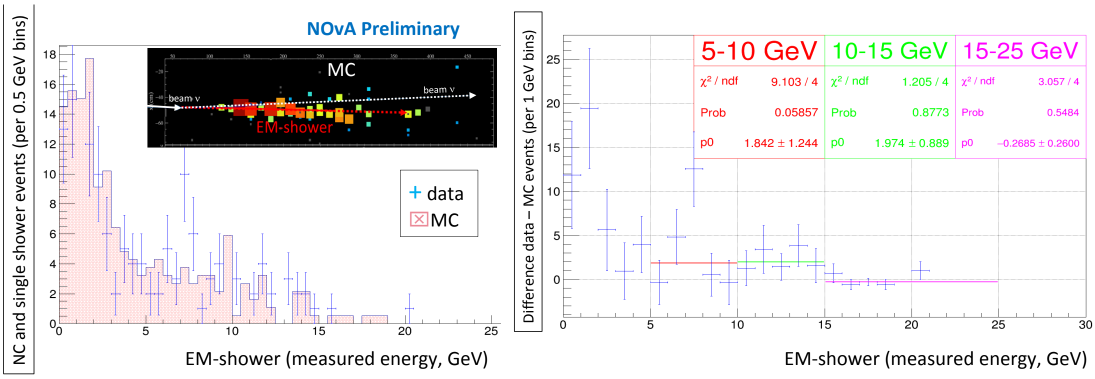

Figure 2: (left) The full energy range spectrum after the NC preselection cuts on data and simulated (MC) events. (left-insert) A simulated (MC) beam-ν_e scattered off of an atomic electron. The ν_e track is artificially displayed. Within the data we cannot distinguish signatures between beam-ν_e and LDM. (right) Shape difference by subtracting the simulated (MC) from the data spectrum. For all three studied energy bands, in this sample, the average is consistent with no excess events from any LDM candidates.

Further studies are warranted, with the full data-set of the first year NOνA run, as well as investigations to the stability of identification efficiency as a function of energy and the purity of the preselection cuts in the high sidebands from the ones they were designed for.

4 Outlook

Further upgrades will bring the intensity to 700 kW within 2016. The projected integral beam is 5×10^{21} POT within the 6 years of the NOνA run plan (see [4]). Regardless of what LDM model each favors, a model-agnostic attitude searching in the excess from the predicted rate can help us probe LDM scattering down to pico-barn cross sections. Also, comparing with the recent results from MicroBooNE will be very interesting. There are also other motivated LDM channels producing particles that may decay in the near detector volume making these exotic searches a full research program at the NOνA-Near Detector and others future experiments. The searches with the NOνA ND though will be ten years in advance of any other [3, 7] proton beam-dump search at these LDM mass ranges.

Acknowledgments

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