

# New light weakly-coupled particle searches in a neutrino detector

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**Abstract.** Neutrino detectors at the accelerator machines of the Intensity Frontier in particle physics are becoming commonplace. As their capabilities are being understood, they seem to have the potential for studies beyond the neutrino oscillations measurements. Besides these primary neutrino physics goals, a number of exotic searches can be done with such detectors in general, and the NOvA detectors that we present here, as a particular example. Specifically, we focus on simulating signatures in NOvA experiment's Near-Detector (300 ton, 900 m from the NuMI target of Fermilab) that correspond to beam-generated new physics states from hidden sectors, dark sectors, axion-like particles, heavy or sterile neutrinos, and heavy photons. As there are no physics generators that can inherently include such states, along with the mainstream production branches, we present here the initial stages of an effort to incorporate these signatures manually in the overall simulation framework of the NOvA experiment. For this, we discuss examples and examine the potential and challenges for detecting such signatures.

## 1. Introduction

The Intensity Frontier (IF) is a world-wide initiative and the Project X [1] machines are a powerful tool consisting of a number of proton accelerators being built at the Fermi National Accelerator Laboratory facility in Illinois, USA. They will be the drivers and sources of high intensity proton, muon, neutron and neutrino beams that will be used to study rare-event phenomena. The NOvA experiment at Fermilab will use a 120 GeV proton accelerator complex at 700 kW producing the NuMI (Neutrinos at the Main Injector) neutrino beam to lead in the measurement of appearance of electron-neutrinos and anti-neutrinos [2]. These machines also have the potential to open the door into what has come to be known as the “New Physics” realms. New theoretical models and ideas of extensions of the Standard Model and the next new physics are widely discussed within the current high-energy literature. They describe exciting ways to reconcile the new discoveries at the Large Hadron Collider of the Higgs boson as they relate to the world observations of the unanswered question of the mass, the force unification, the nature of the dark matter and the matter-antimatter inconsistency of the universe. One of the more exciting and exotic candidates for these options are New Light ( $\sim$ GeV) Weakly-Coupled particles (NLWCp).

The motivation for various NLWCp cases comes naturally from extensions of the SM. Concepts such as Hidden or Dark Sectors in nature suggest that the constituents of the particle structure of these sectors are neutral with respect to the Standard Model charges. Models of global broken symmetries give rise to the elusive Axion ( $\sim$ meV) and other Axion-like-particles (ALPs) which do not bind their masses with the weak scale coupling. There are also concepts of Heavy Photons whose decay may be a source of Dark Matter in a Dark Sector and Heavy Neutrinos that may complete the puzzle of the CP violation in the lepton sector. They can all, potentially, be produced in the high intensity beams of  $10^{15}$ /s of protons or electrons on carbon, mercury or other high-Z material



at the target or beam-dump. A brand new particle discovery will be overwhelming proof of the existence of the postulated New Sectors in nature, and will not only define the High Energy physics research in this century, it will give us the first dynamic coupling, as in the case of Axions, and a view into the nature's intentions, as in the case of Hidden Sectors, where there are no reasons to have any anthropic motivated fine tuning of parameters.

## 2. Expecting NLWCp in NOvA experiment

The theoretical motivation for expecting these discoveries at the proton accelerator fixed-target/beam-dumps is well described in IF literature [1-3]. Therefore, in this, we summarize only some of the motivations for using the neutrino detectors to search for such states. There is a significant arrangement of short- and long-baseline neutrino oscillation experiments using intense proton beams on fixed targets separated from the near (or main) neutrino detector by several hundred meters of earth or decay volumes and absorbers [1, 2]. Their primary design of creating focused and intense neutrino beams already provide significant sensitivity to nonstandard interactions and specifically to heavy and sterile neutrinos.

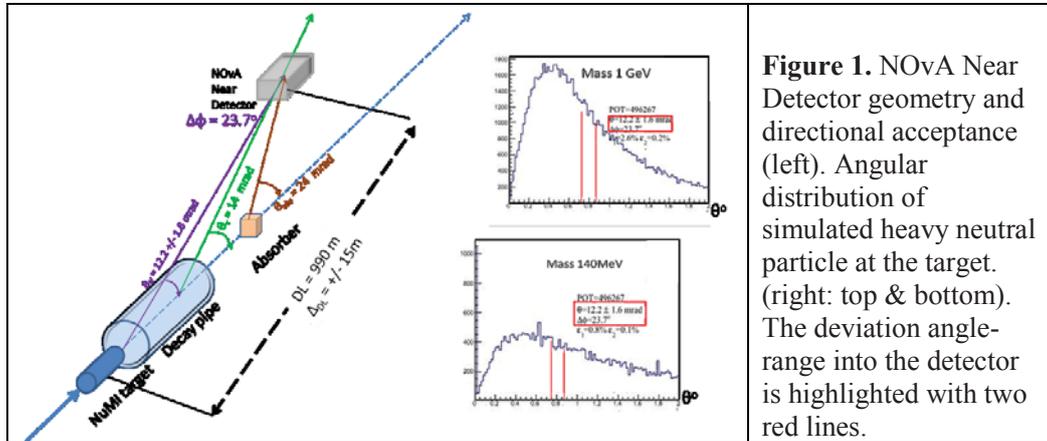
Various extensions to the standard model, including most grand unified theories, predict Neutral Heavy Leptons (NHLs, or heavy neutrinos) which can mix with the standard (light) neutrinos to interpret the LSND/MiniBooNE anomaly [4]. A 40-80 MeV sterile neutrino decaying into a light neutrino and photon or a 50 MeV neutrino could be produced in collisions with matter through Z- and photon-mediated processes [4]. If the mass is bigger than 140MeV, then other decay channels are also possible. For a mass region 0.25-2.0 GeV, the charged coupled decays are either through a light neutrino and two charged leptons, a lepton and two quarks, or into three neutrinos [4]. Similar decay models exist for the charged current decays in this mass ranges. NOMAD [5] sets stringent limits of  $10^{-15}$  for the hypothetical single photon if it has a momentum distribution similar to that of a photon from the coherent neutral pion decay. However, using the enhanced flux  $10^{15}$  POT/sec from NuMI beam and the advanced NOvA reconstruction algorithms, we can attempt detecting this heavy neutrino at the NOvA near detector.

## 3. Signatures in the NOvA Near detector

The NOvA experiment is made of two functionally identical detectors positioned off-axis by 14 mrad in front of the powerful NuMI beam of Fermilab producing neutrinos of peak energy 2GeV. The design of NOvA, of long extruded PVC tubes/cells arranged in a cross orientation, has been described in several places including reference 2. From the pair, the Near Detector (ND) of 18,000-cells and 300-tons is positioned 990 m from the NuMI beam-target. It is designed to be sensitive to muonic and electron neutrino interactions in its detectors. NLWCp signatures would appear in the detector signals as neutral current processes of the incident particle on nucleons or orbital electrons, or decays of the new particles into dilepton pairs or pion-muon combinations. The beam neutrinos have a specific energy distribution and mass (1-3 GeV in the detector's direction) but the search of NLWC particles from NuMI is model-agnostic and therefore, the energy is an open parameter. It is constrained only from geometrical and detection efficiencies. This translates to differences in kinetic energy share at their production vertex which, in turn, defines the sensitivity to production models.

In order to identify and understand the sensitivity limits of the ND to such particles, a campaign of creating specialized analysis packages has started. They can be added to the NOvA analysis framework, to supplement its capability to recognize NLWCp among neutrino interactions. The first stage of this effort includes simulations of the beam products. The beam simulation is an effort to include neutral particles with mass and kinetic energy consistent with production-channel models. It aims to create the simulation of the expected energy spectrum and angular (spatial/directional) distribution of the expected NLWCp as they travel from the target or a point along the decay volume, towards the ND. A sample of this, we show in figure 1 (right) where the angular distribution of two types of particles are shown as they were simulated by the beam-product algorithm FLUKA [6]. The two arbitrarily chosen masses are shown here as a sample of these distributions. A

more generalized algorithm is still under design, one that would generate NLWCp in the form of neutral particles of any mass and determine its directional distribution probability.

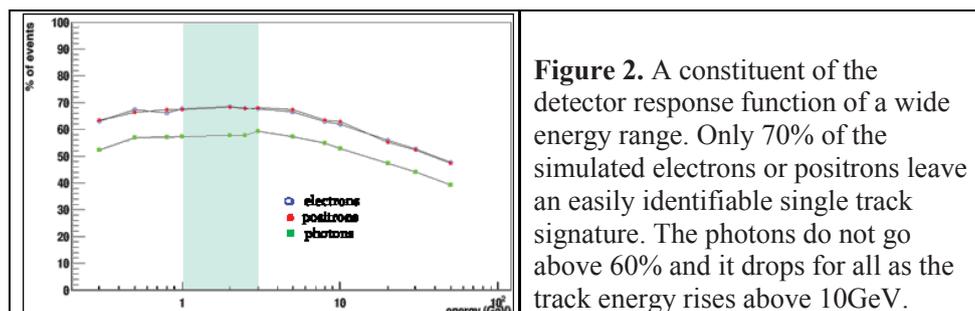


**Figure 1.** NOvA Near Detector geometry and directional acceptance (left). Angular distribution of simulated heavy neutral particle at the target. (right: top & bottom). The deviation angle-range into the detector is highlighted with two red lines.

The other part of this work is the simulations of signals. It is consistent with the most probable signatures of NLWCp in the NOvA near detector. It aims to provide an understanding of the detector efficiencies in geometry, in containment, in energy resolution. Also, the software reconstruction capabilities will have to be much wider in energy (and masses) than the baseline NOvA reconstruction is targeting [7]. The figures 2 and 3 show aspects of the detector response to simulated neutral current interactions. They come from simulated single electron and positron tracks that could be either scattering signatures or ones from the lightest dilepton decays of an NLWCp. Also, there are examples of single photons from the decays of heavy or sterile neutrinos. At this stage, the simulations are not exhaustively representing complete signatures that could challenge the analysis framework but rather the components of the detector response that affect the overall sensitivity of the detector.

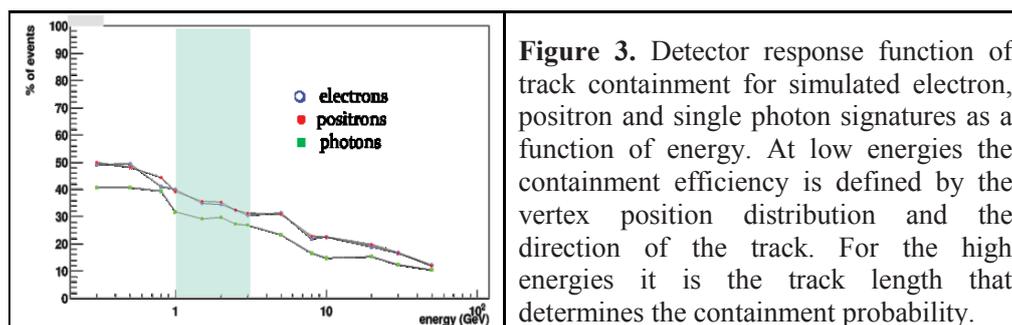
Figure 2 shows a distribution of the fraction of simulated events that leave a single track in the detector as a function of their initial energy. The maximum of the distribution is about 70% and it peaks at the region of the NOvA energy range of interest. It drops significantly at higher energies as the showering becomes a big part of the signature. Of course, the single-photon simulation, where showering is more prominent, includes fewer single track events, even at the region of 1-3 GeV (highlighted in fig. 2 and 3) for which the detector is optimized. The background to the single photon signal is dominated by the asymmetric decay of neutral pions produced either in a coherent neutrino-nucleus interaction or in a neutrino-nucleon neutral-current deep-inelastic scattering or in an interaction outside the detector fiducial volume.

Even from this preliminary effort, there are signs of the sensitivity limitations. The neural nets that perform identification are trained easily for tracks but require substantially larger libraries of realistic or (better yet) real shower events. That would involve a test beam calibration which is not possible of the NOvA near detector.



**Figure 2.** A constituent of the detector response function of a wide energy range. Only 70% of the simulated electrons or positrons leave an easily identifiable single track signature. The photons do not go above 60% and it drops for all as the track energy rises above 10GeV.

Figure 3 shows distributions of full-track containment cases over the same wide-energy range and for the three different types of particle products. As the track and/or shower length/size is a function of the energy, the drop in containment efficiency at the high energies for all types of particle signature-products is large as expected. For this aspect of the detection sensitivity there is no possible compensation from extra investment in enhancing reconstruction or particle-identification software. The detector size defines this sensitivity as its distance from the target defines the decay path sensitivity to the NLWCp lifetime, as in figure 1.



**Figure 3.** Detector response function of track containment for simulated electron, positron and single photon signatures as a function of energy. At low energies the containment efficiency is defined by the vertex position distribution and the direction of the track. For the high energies it is the track length that determines the containment probability.

#### 4. Summary

The extremely exciting subject of the new light weakly-coupled particles and non-standard neutrino interactions that has been postulated in papers for years, now, is about to come to the forefront of physics research with the introduction of new powerful accelerators from the Intensity Frontier. The beginning of an effort to pave the way, before the creation of dedicated experiments, is presented here. The NOvA Near Detector is a system that can be used in the first stages of this search for NPWCp. Its limitations due to its design for neutrino detection do not prevent us from investing a wide range of mass/energies of NLWCp by studying the data it will collect, and with this, strengthen the physics program at the facility.

#### References

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