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Muon Neutrino on Electron Elastic Scattering in the NOvA Near Detector and its Applications Beyond the Standard Model

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Abstract. Using the NuMI beam at Fermilab and the NOvA near detector, we study the process by which a muon neutrino elastically scatters off an electron in the detector to produce a very forward going electromagnetic shower. By comparing dE/dx for various particle hypotheses for both longitudinal and transverse directions in a multilayer perceptron neural network, we trained a Particle ID algorithm to identify the scattered electron in an inclusive dataset. Muon-neutrino-on-e elastic scattering provides a clean, purely leptonic process free from nuclear effects for understanding neutral current scattering and constraining the NuMI beam flux. Also, this technique can be applied in two broad areas of beyond the standard model physics: a large neutrino transition magnetic moment and light dark matter particles produced in the NuMI target, both of which would create an energy dependent enhancement in the elastic scattering cross section.

1. Introduction
We discuss the process by which a muon-neutrino exchanges a neutral boson with an electron in the NOvA near detector. The scattered electron forms a very forward-going electromagnetic shower as shown in Fig. 1. This process provides a traditional method to understand neutral current scattering and to constrain the neutrino flux since it is a clean, purely leptonic process free from nuclear effects. The low-Z materials used in the NOvA detectors and its fine transverse cell size (Fig. 2) ensure good angular resolution for electron showers, as one radiation length is about six planes and the Molière Radius is 2-3 cells [1, 2].

2. Neutrino-Electron Elastic Scattering for Flux Constraint
We use a multilayer perceptron neural network for particle ID training, a method similar to that used in the first results of ν_e appearance analysis in the NOvA experiment [4]. The log-likelihood of the observed dE/dx matching one of multiple particle hypotheses (e to π^0, γ, $\pi^{\pm}$, p, n and μ) for both longitudinal and transverse shower direction is used to identify an elastically scattered

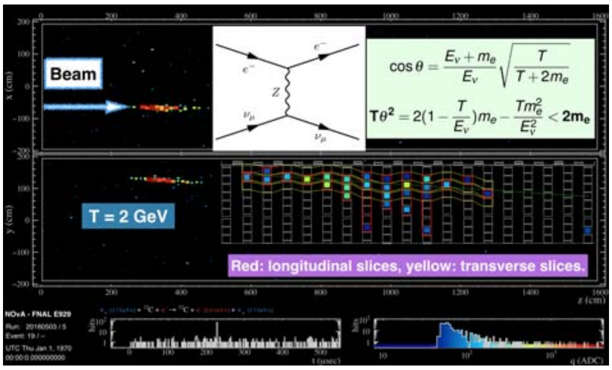

Figure 1. Event display of a 2 GeV scattered electron and likelihood identification.

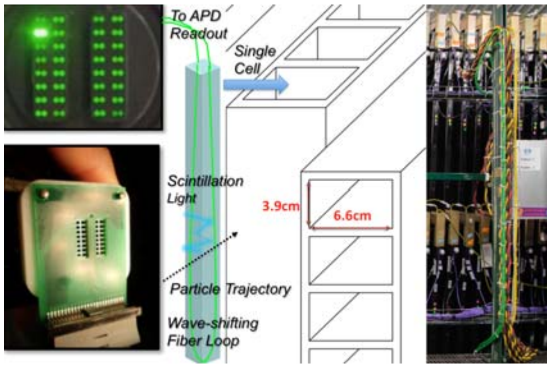

Figure 2. Structure of the NOvA detectors [3].

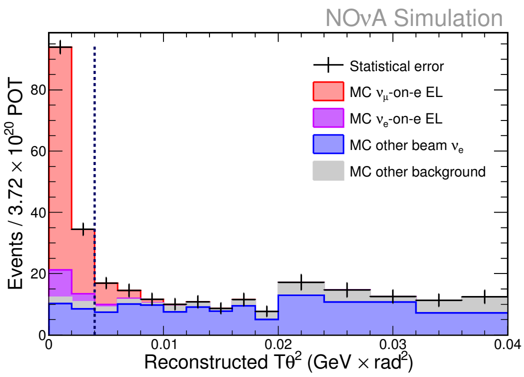

Figure 3. $T\theta^2$ distribution found using the NOvA second analysis Monte Carlo [6].

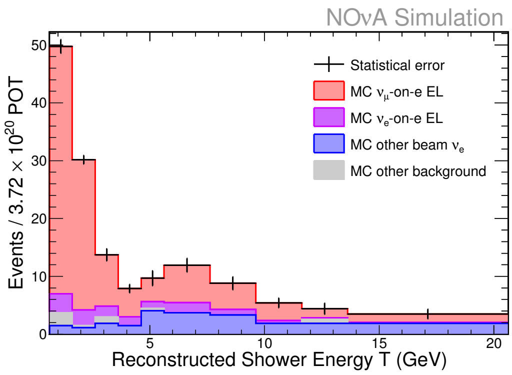

Figure 4. Reconstructed electron energy distribution for ν-e elastic scattering for electron recoil energy $T > 0.625\,\text{GeV}$ after $T\theta^2$ cut shown in Fig. 3.

electron in an inclusive dataset. The ν-e elastic scattering events have the kinematic feature that $T\theta^2 < 2m_e$ [5]. Here θ represents the reconstructed angle between an incoming neutrino and the scattered electron, and T is the kinetic energy of the electron. Pion induced showers are removed by comparing the dE/dx in the first 4 planes with those from electron showers. After selecting events with $T\theta^2 < 0.004$ $(GeV \times rad^2)$ (Fig. 3), the shower energy T distribution (Fig. 4) will constrain the neutrino beam flux and relative abundance of parent kaon and pion once a correspondingly large data set is collected. The tuned MC will then be the basis for predicting SM background rates for neutrino magnetic moment and lightweight dark matter searches.

3. Muon Neutrino Magnetic Moment

It is unclear whether neutrinos are Dirac or Majorana particles. A Dirac muon-neutrino has a tiny magnetic moment value [7], too small to be observed by magnetic scattering in the NOvA near detector. While for Majorana neutrinos, the magnetic moment in models derived from SU(2) symmetry [8] could have $\mu_\nu \approx \mathcal{O}(10^{-9}\mu_B)$ [9, 10], a value which can be tested in the NOvA near detector by using data from three years of running at NuMI design intensity (1.8×10^{21}POT).

When a Majorana muon neutrino scatters off a free electron, it switches its flavor into one of

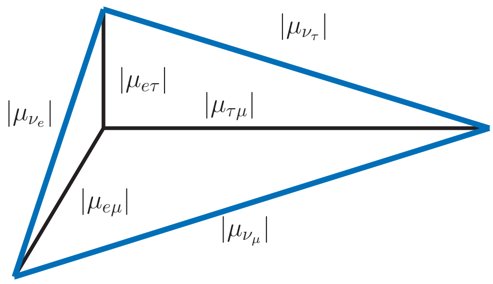

Figure 5. Triangle relations for Majorana neutrino magnetic moments [12].

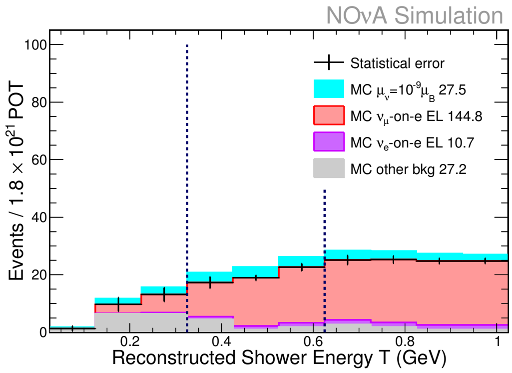

Figure 6. Sensitivity after three years of running at NuMI design intensity in the NOvA near detector.

the other two flavors due to a large transition magnetic moment. Reactor experiments such as GEMMA have measured the μ_{ν_e} upper limits at the order of $10^{-11}\mu_B$ [11]. However, the $\mu_{\tau\mu}$ component shown in Fig. 5 [12] will be better measured in accelerator experiments like NOvA. The purity of the NuMI beam allows NOvA to see the enhanced scattering cross-section of a Majorana muon-neutrino. For a cosmologically interesting value of μ_{ν_μ}=$10^{-9}\mu_B$ [13], we could see 27.5 events above a background of 182.7 (Fig. 6). If limits are set, we can combine the results from reactor experiments to do a joint analysis to constrain the tau neutrino magnetic moment by using $|\mu_{\nu_\tau}|^2 \leq |\mu_{\nu_\mu}|^2 + |\mu_{\nu_e}|^2$ [12], providing constraints on models of the early universe [13].

4. Searching for Lightweight Dark Matter

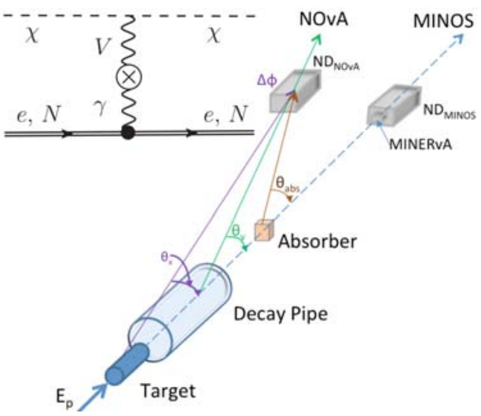

Figure 7. Feynman diagram and detection geometry used in this work.

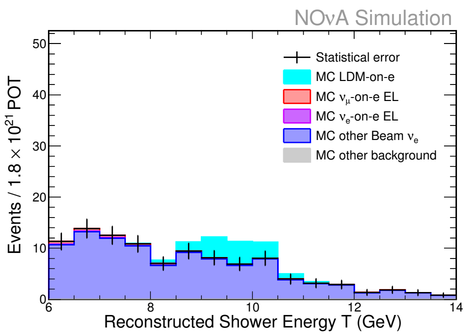

Figure 8. LDM-on-e signals over SM background.

Electron scatters at high (5-15 GeV) reconstructed shower energies could be used to detect some models of Lightweight Dark Matter (LDM) produced in the NuMI target [14] and scattered through a mediator in the NOvA near detector (Fig. 7). As an example, assuming the selection efficiency is analogous to ν-e scattering and using strict Particle ID cuts with an extremely narrow angular fiducial volume surround the LDM beam direction, a model with $m_\chi = 300MeV$ implemented in Pythia 8.1 would yield a clear signal of $\mathcal{O}(10)$ events over SM background for $1.8{\times}10^{21}$POT (Fig. 8).

5. Summary and Outlook

With the latest NuMI flux simulation and the most accurate geometry simulation, we generated a large sample of neutrino electron elastic scattering, 2000 times larger than the available data set. We have an efficient ν-e sample selection technique useful for constraining the NuMI beam flux, and model dependent searches for a neutrino magnetic moment and for lightweight dark matter.

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