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The Shadow of the Ghost: Another Look

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ABSTRACT

The most recent results from the MiniBooNE search for sterile neutrinos are discussed. MiniBooNE has reported[1)] results on anti-neutrino running from a sample of 5.66×10^{20} protons on target. A slight excess of 43.2 ± 22.5 events is observed in the range of estimated energy between 200 MeV and 3000 MeV. Assuming this small excess to be due to neutrino oscillations, a simple two-neutrino model fits the data much better than our estimate of the background alone. We estimate a probability of only 0.5% that our estimate of the background alone could have produced an oscillation fit likelihood as large as the data.

1. Introduction and Motivation

The neutrino was discovered over 50 years ago, and it is still the least understood of all of the quarks and leptons, even the nature of the correct quantum field describing them is still unknown. Because neutrinos have no electric charge to conserve, they might be described by one of several possible fields, for example Majorana, Weyl, or Dirac spinors.

The right-handed chiral parts of the quarks and charged leptons are $SU(2)_L$ gauge singlets, so they do not interact weakly, and furthermore, they have identically the same mass as their left handed counterparts. In an analogy to the the quarks and charged leptons, the right handed neutrino components would be without interactions, save gravitation, and would make them nearly impossible to observe. Furthermore, since they are neutral fermions, the masses of the right handed states are not constrained by electric charge conservation to be the same as their left handed components. Since there is no direct experimental evidence for the existence of sterile neutrinos, and the search for them continues. While neutrinos have been dubbed the "ghost particles" a fitting moniker for sterile neutrinos might be "the shadows of the ghosts".

In addition, if the right handed components are without any interaction other than gravity, they would not be necessarily constrained to the 4 dimensional brane determined by the standard $SU(2)_L \times U(1) \times SU(3)_{color}$ and might propagate in the bulk. Such theories allow the sterile neutrino to, for example, take shortcuts in higher dimensional spaces and cause complex and interesting resonant oscillation

phenomena[19].

1.1. Sterile Neutrinos in Cosmology and Astrophysics

Sterile neutrinos generally have a large impact on cosmology and astrophysics. In astrophysics, neutrinos play an important role in core collapse supernova (Type.II SN), where more han 99% of the energy radiated by the collapse is in the form of neutrinos. Indeed, neutrinos were observed coming from the nearby supernove 1987a by the IMB[4] and Kamiokande[5] experiments. Type II SN explosions are thought to be the best potential candidate site for the rprocess to occur, thereby producing all of the naturally occuring elements heavier than iron, such as uranium. The current models of Type II SN preclude that possibility. The intense flux of neutrinos emmitted by the supernova break up the deuterium via their neutral current interactions with it thereby suppressing the r-process at its first stage. A sterile neutrino with a Δm^2 near 1 eV^2 and mixed with active neutrinos has been shown[3] to allow the r-process to take place.

Sterile neutrinos also might play a role in cosmology. Sterile neutrinos with a mass of around 1 GeV or greater might produce the baryon asymmetry seen in the universe through CP violating oscillations just prior to the electro-weak phase transition in the early universe[6]. The leading candidate for dark matter is the sterile neutrino. The latest simulations of galaxy formation with cold dark matter produce too many clusters of dark matter which would seed dwarf galaxies at a level not observed locally. A lighter form of dark matter, for example a 1-5 keV mass sterile neutrino might solve this difficulty. Sterile neutrinos might also be responsible for the extra degrees of freedom that comological fits and that big bang nucleosynthesis seem to prefer.

It might be that the effects of sterile neutrinos are not directly observable by experiment, in which case they will forever remain speculative possibilites, however we are far from being in that situation at the present time.

1.2. Looking for Shadows

Sterile neutrinos can manifest themselves in a variety of ways depending upon their masses and mixings with active neutrinos. While they do not participate in the standard weak interaction, they might interact via a heavier set of $SU(2)_R$ gauge bosons. Six neutrinos, 3 active and three sterile, would mix via a 6x6 unitary matrix. However, the sterile-sterile mixing is not observable, and hence the number of observable parameters in oscillations is less than that of a 6x6 unitary matrix.

There are other scenarios where heavier neutrinos could be produced in large detectors and then decay in the same detector[7]. These are largely ruled out by LEP experiments[22][24], neutrino experiments[23], and pion or kaon decay experiments. Never the less, there are regions of mxing and mass that are still allowed, regions that

could explain some of the anomalies in the LSND/MiniBooNE/T2K data.

A sterile neutrino of roughly 10 keV could be a viable dark matter candidate and might decay into a single photon plus a lighter active neutrino. This would produce a mono-energetic photon signal observable by xray detectors aboard satellites[8,9].

There are may ways in which sterile neutrinos could manifest themselves in the universe and in the laboratory. In the following we discuss some of the anomalies in short-baseline neutrino oscillation experiments that could be explained by light sterile neutrinos.

1.3. Neutrino Oscillations and the νMSM

The last several decades have yielded a wealth of infomation about active neutrinos. It is now clear that the active neutrinos are mixed with each other and have masses[10,11,12,13]

We shall call this standard picture the minimal standard model of neutrinos, or νMSM[20,21]. The νMSM does not contain the gauge singlet right handed component of the neutrinos, which is a reasonable position to take since there is no direct experimental evidence for their existance. There are theoretical reasons to believe that the right handed neutrino components exist, but have been made very heavy through a "see-saw" mechanism.

2. Hints for Physics Beyond the νMSM in Neutrino Oscillation Experiments

While there is no concrete evidence for sterile neutrinos in neutrino oscillation data, there are a number of hints or anomalies in single detector experiments such as is described in the papers by LSND[16] and MiniBooNE[15,14]. The resolution of those anomalies will happen when two detector systems can be implemented such as the BooNE proposal[17] or the ICARUS-PS proposal[18].

Figure 1 shows the distribution in reconstructed neutrino energy of the MiniBooNE oscillation sample for neutrino mode. Figure 2 shows the distribution in reconstructed neutrino energy of the MiniBooNE oscillation sample for antineutrino mode.

Figure 3 shows the latest data from MiniBooNE antineutrino-mode running corresponding to 8.56×10^{20} protons on target (POT). There are several assumptions necessary to make these plots, one that there is no disappearance in the background, and second, that the source neutrino species is unique, e.g. oscillated electon antineutrinos come exclusively from muon antineutrinos.

There is some similarity and overlap between the L/E plots that suggest that oscillations might be taking place. Again, without a near, second detector, it is not possible to say whether or not they are due to oscillations.

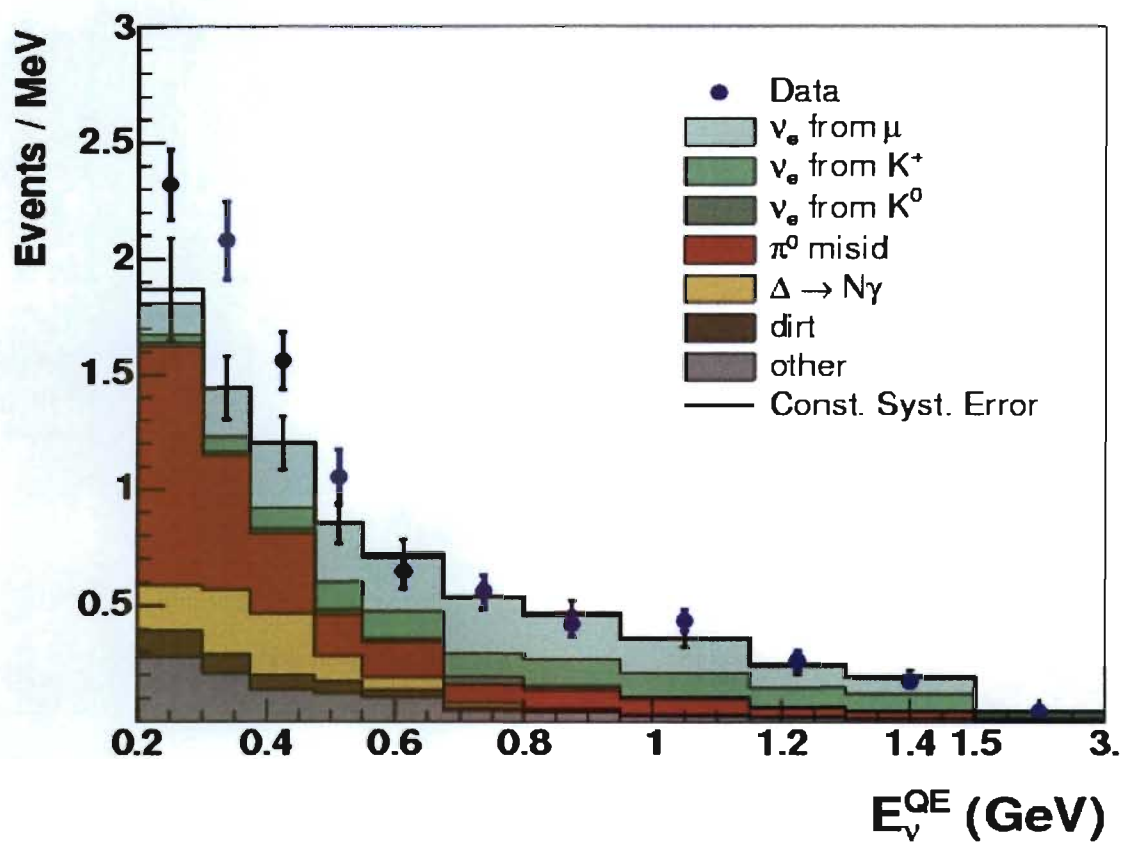

Figure 1: MiniBooNE neutrino mode nue-like selection (oscillation sample) corresponding to 6.46×10^{20} protons on target.

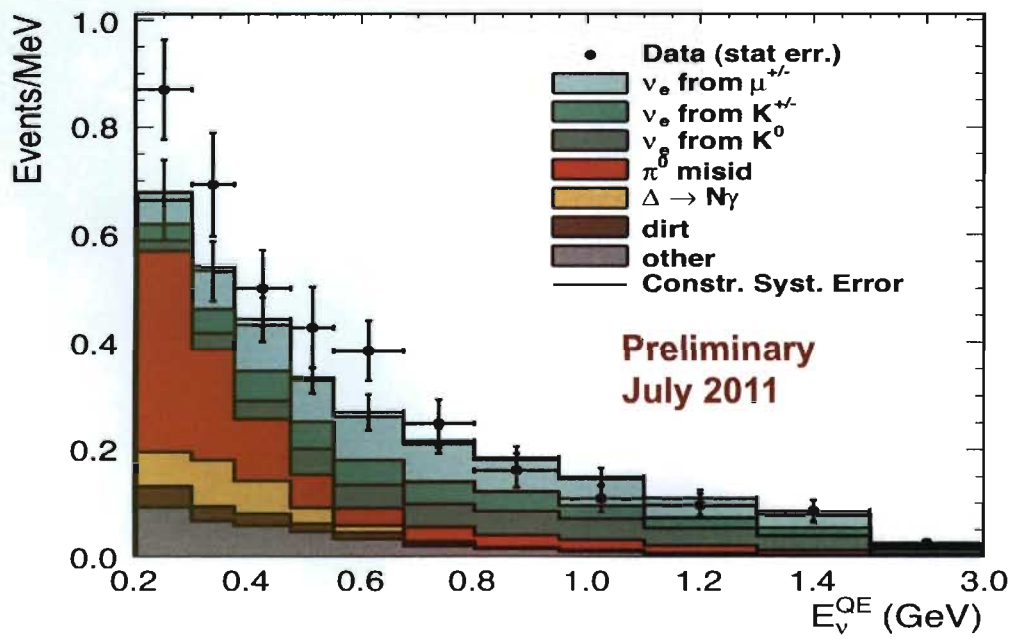

Figure 2: MiniBooNE antineutrino mode nue-like selection (oscillation sample) corresponding to 8.56×10^{20} protons on target.

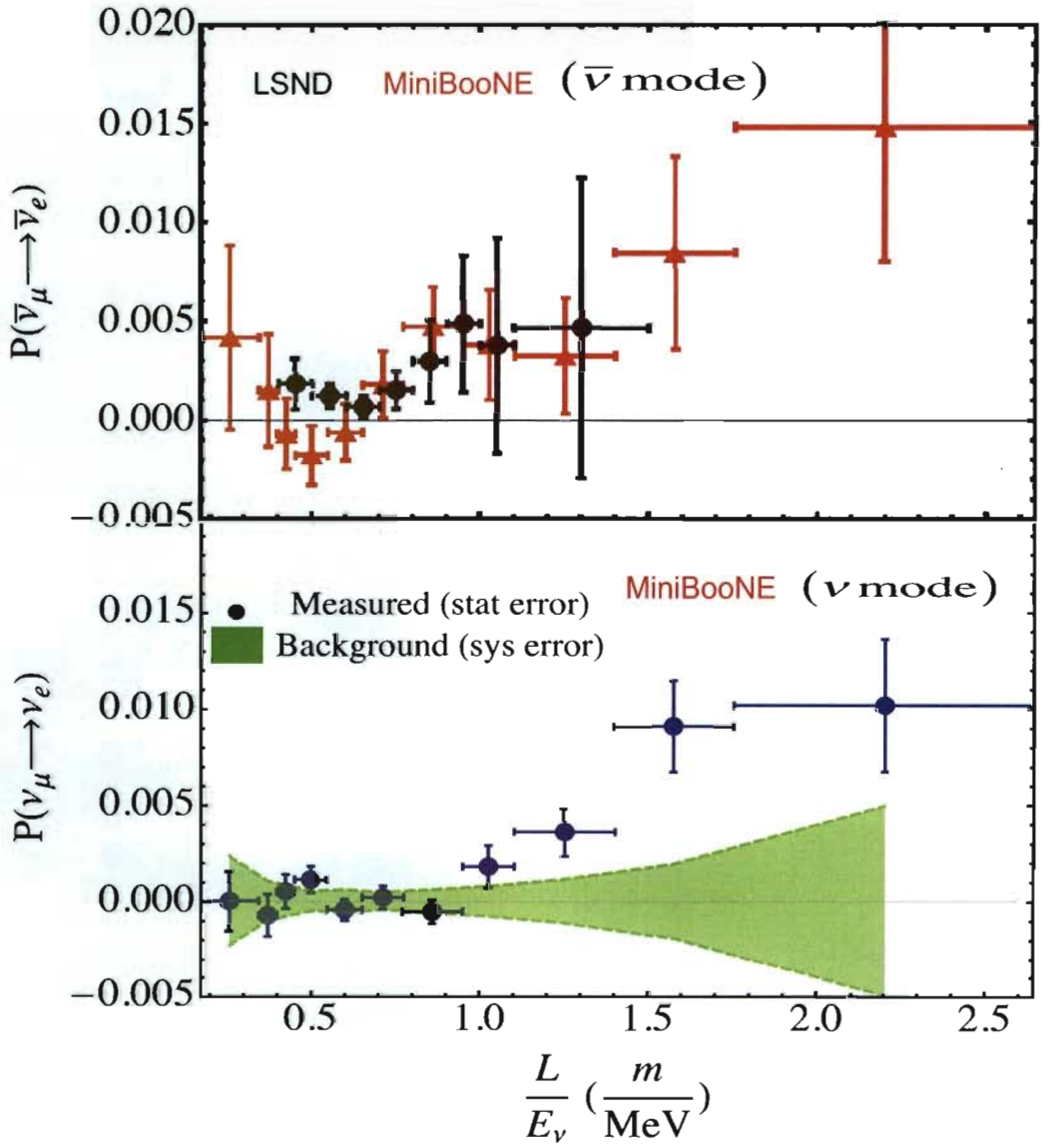

Figure 3: LSND and MiniBooNE anomalies in electron neutrino and anti-neutrino appearance. The data corresponds to 6.46×10^{20} protons on target in neutrino mode, and 8.56×10^{20} in antineutrino mode.

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