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A Proposal for
MiniBooNE+: A new investigation of $\nu_\mu \to \nu_e$ oscillations with improved sensitivity in an enhanced MiniBooNE experiment

MiniBooNE+ Collaboration

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1 Executive Summary

In this proposal, we describe a plan for further running of the MiniBooNE experiment with the addition of scintillator to the existing detector. This effort, "MiniBooNE+", will improve upon the current MiniBooNE signal for neutrino oscillations by adding further neutral-current/charged-current (NC/CC) discrimination of candidate events in an additional electron-neutrino appearance search.

A combined analysis of the MiniBooNE neutrino and antineutrino data shows a 3.8σ excess and is fairly consistent with the excess seen by the LSND experiment, the original motivation for MiniBooNE. This may be evidence for beyond-SM sterile neutrinos. However the shape of the events in energy requires multiple sterile neutrinos for a satisfactory fit, which then leads to tensions in other neutrino data sets, and an explanation for this MiniBooNE excess continues to elude a consensus theoretical explanation. The need for a resolution to the issue is high. As stated in the recent Snowmass neutrino report *"The discovery of new neutrino states, for example, would revolutionize our understanding of particle physics. Definitive tests are clearly needed and concrete efforts are already underway."* MiniBooNE+ should be one of these concrete efforts. It is of modest expense and builds upon the monetary and intellectual investment into MiniBooNE of the last decade.

The combined MiniBooNE 3.8σ excess is highly significant statistically at 7.0σ, so further running with the same experimental configuration will not help. The only way to improve the situation is to reduce backgrounds and the related systematic errors. At low energy, in the region of the largest event excess, the NCπ^0 and NCγ channels dominate. These are both constrained in related MiniBooNE measurements and further theoretical work has strengthened those conclusions. However, more significant and highly cross-checked evidence for the neutrino appearance would be game-changing for the Standard Model and merits the effort proposed here.

The addition of scintillator to MiniBooNE enables reconstruction of the 2.2 MeV γ from neutron-capture on protons following neutrino interactions. Charged-current neutrino interactions, at low-energy where the MiniBooNE oscillation excess is observed, should have associated neutrons with less than 10% probabability. This is in contrast to the neutral-current backgrounds which will have associated neutrons in approximately 50% of events. In addition, these predicted neutron fractions will be measured in MiniBooNE with muon neutrino proxy events for both the charged- and neutral-current channels, thereby greatly reducing systematic uncertainty on those predictions.

A veto on events with one or more detected neutrons will reduce the neutral-current background events substantially with only slight reduction in signal. At the same time a measurement of neutron multiplicity in the oscillation candidate and muon neutrino proxy samples will reduce the systematic uncertainty in the background prediction. These factors will increase the significance of the oscillation excess, if it maintains in the new data set, to the 5σ level.

This new phase of MiniBooNE ("MiniBooNE+") will enable additional important studies such as the spin structure of nucleon (Δs) via NC elastic scattering, a low-energy measurement of the neutrino flux via $\nu_\mu\ {}^{12}C \rightarrow \mu^-\ {}^{12}N_{\text{g.s.}}$ scattering, and a test of the quasielastic assumption in neutrino energy reconstruction. These topics will yield important, highly-cited results over the next 5 years for a modest cost, and will help to train Ph.D. students and postdocs. The (Δs) measurement can be completed with a shorter run of 2×10^{20} protons-on-target as can the neutron fraction in muon neutrino proxy events. This would provide a short-term milestone to produce a physics result and check the viability of the longer-term oscillation search.

This work will be complementary to the efforts of the upcoming MicroBooNE experiment. This proposed method focuses on nuclear recoil with a large event sample. MicroBooNE will look precisely at the lepton vertex for background rejection, but will likely be limited by their smaller

fiducial volume and event rates. In addition, MiniBooNE+, running in same neutrino beam at the same time, can help MicroBooNE monitor the neutrino flux and any unexpected changes in the beam. Continued running of MiniBooNE+ will also preserve and cultivate the expertise gained on the neutrino beam and interactions over the last 10 years and published in 26 refeered papers. This will help to assure that MicroBooNE and the future Fermilab neutrino program is a continuing success.

> *We are requesting approval for MiniBooNE+ which requires* 6.5×10^{20} *protons on target. The* Δs *measurement and calibration of the oscillation event neutron fraction can be obtained with* 2×10^{20} *protons on target providing an early test of the viability of the new oscillation measurement along with a physics result. We request to begin this new phase of running in mid-2014, concurrently with the MicroBooNE experiment.*

Progress since LOI

A Letter of Intent [1] was submitted to the Fermilab PAC in the Fall of 2012. Since that time, we have progressed on MiniBooNE+ in the following areas.

- Funds for the required 300 kg of PPO ($75k) have been obtained from NSF–Nuclear Physics.
- The rate of neutron-capture background events has been measured to be 0.5 $s^{-1}m^{-3}$ in existing MiniBooNE data. Scaling to rate expected for MB+ yields a rate of 4 $s^{-1}m^{-3}$, consistent with that measured by LSND and with our previous estimates.
- The maximum solubility of PPO in MiniBooNE mineral oil has been measured to be 40 g/L, well-above our proposed 0.3 g/l concentration for MiniBooNE+.
- The compatibility of detector components has been determined to be adequate by soaking them in a 20 g/L PPO/mineral oil mixture for 11 months. No change in the oil or materials was detected.
- An improved estimate of the expected neutron-multiplicity in background events has been obtained by combining new, more detailed, theoretical calculations with an estimate of neutron response in the MiniBooNE detector. The new estimate for fraction of NC background events with a detected neutron capture is 56%, consistent with our initial estimate of 50%. Our estimate for the fraction of CCQE signal events has increased slighty to 8-20% (from 250-1000 MeV) due to "QE-like" ν_e CCπ events.
- Application of a n-capture veto strategy will result in a background reduction to 79% of the current background level. Background-signal differences in neutron multiplicity should allow that these variables can reduce the background systematic error by a factor of 2 from current values. This level of background level and systematic error will increase the oscillation sigificance to the 5σ level in repeated oscillation search, if the excess is indeed due to ν_e appearance oscillations.
- Further studies of event reconstruction with increased scintillation have been performed with full detector event simulations. These indicate that the current level of particle ID may be maintained for reconstructed neutrino energy up to 1 GeV.
- A complete Monte Carlo simulation of a 2×10^{20} POT Δs measurement via the NC-elastic proton-neutron ratio yields a predicted error of ± 0.06, competitive with existing deep-inelastic scattering measurements.

- The collaboration strength has been demonstrated by successfully restarting the MiniBooNE detector and beamline in the Fall of 2013. On the analysis, we have are successfully running the detector Monte Carlo simulation and analysis code in MiniBooNE+ mode and have recruited new students and postdocs for this work.

Supporting details of the items are explained in the following pages of this proposal.

2 Introduction

The MiniBooNE experiment has, for the last 10 years, searched for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ in the Booster Neutrino Beamline at Fermilab. The beam was shut down in April 2012 to enable the Fermilab accelerator complex to be upgraded in preparation for delivering higher beam power to the NOvA experiment. Before the shutdown, MiniBooNE completed an antineutrino phase of running which brought the total amount of beam delivered to the experiment to 11.3×10^{20} protons on target (POT) in antineutrino mode and 6.5×10^{20} POT in neutrino mode.

Both $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation analyses have been conducted with this data individually [2]-[5] and recently as a combined data set with the latest updates to the antineutrino data [6]. There is an excess of events over the calculated background (Fig. 1) in both neutrino (3.4σ) and antineutrino (2.8σ) modes. The combined data set contains a total excess of 240.3 ± 62.9 (3.8σ) events. A two-neutrino fit to the combined data set yields allowed parameter regions (Fig. 2) which are consistent with oscillations in the 0.01 to 1 eV^2 Δm^2 range and are consistent with the regions reported by the LSND experiment [7].

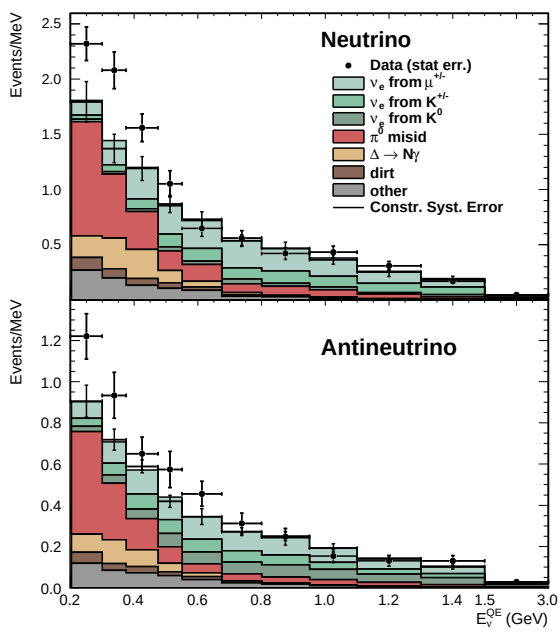


Figure 1: The neutrino mode (top) and antineutrino mode (bottom) reconstructed neutrino energy, E_ν^{QE}, distributions for data (points with statistical errors) and predicted background (histogram with systematic errors).

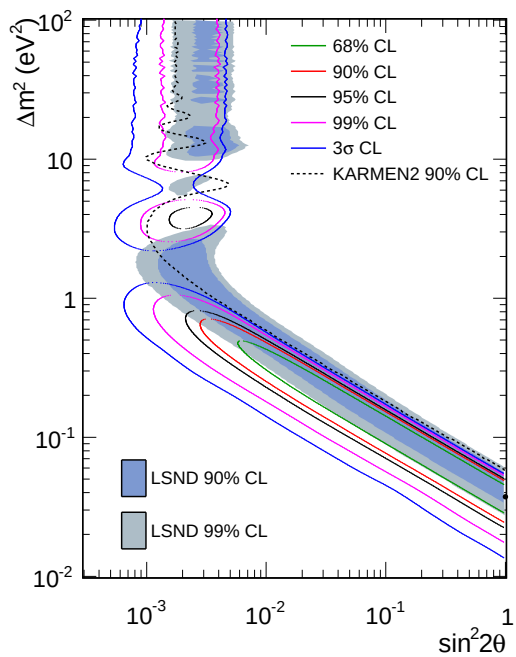


Figure 2: MiniBooNE allowed regions in combined neutrino and antineutrino mode for events with $200 < E_\nu^{QE} < 3000$ MeV within a 2ν oscillation model.

This may be evidence for sterile neutrinos and confirmation of the original LSND observation. However, a few model inconsistencies give pause to that simple interpretation. While reasonably compatible with the expected rate from LSND, the shape of the excess in energy is only marginally compatible with L/E in the neutrino data. In addition, sterile neutrino fits can only explain the MiniBooNE data with the addition of at least 2 new sterile Δm^2 and strong tension with other disappearance data (eg. [8, 9]). However, other anomalies exist in this baseline region such as

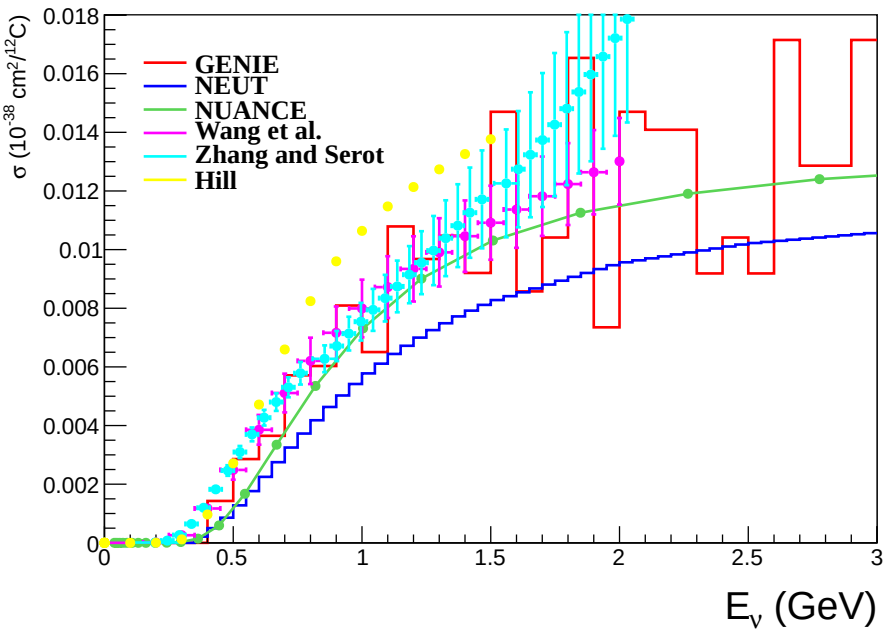


Figure 3: Neutrino carbon NCγ production cross section as function of neutrino energy as calculated by Wang et al. [23], Zhang and Serot [21], and Hill [14] and compared to three neutrino event generators. The NUANCE curve corresponds to the MiniBooNE estimate for this process. Note that the most important region in this plot is at the MiniBooNE flux peak of 800 MeV. The Zhang and Serot model is acknowledged to contain divergent terms above 1.5 GeV

the deficits of reactor $\bar{\nu}_e$ events [10] and radioactive-source ν_e events as observed in the SAGE and GALLEX experiments [11]. While not simply interpreted, these observations are potentially revolutionary for particle physics and, as stated in the recent Snowmass neutrino report [12], *"Definitive tests are clearly needed and concrete efforts are already underway."*

2.1 Further investigation of the MiniBooNE NC γ background

When the MiniBooNE neutrino result appeared in 2007, a paper by Harvey, Hill, and Hill [13] pointed out that an overlooked diagram coupling the photon, Z-boson, and ω-meson could be contributing to the background at a rate larger than the MiniBooNE background estimate of NC γ. Since that paper, work on this particular channel has continued with one of the authors of the original paper [13] along with several other groups [14]-[23]. Representatives from these groups have recently met to summarize the situation at an INT workshop at the University of Washington [24].

In summary, there is consensus between those theory groups that the original diagram initially proposed in Ref. [13] as a possible explanation to the MiniBooNE excess is not the dominant contribution to NC γ production and is most likely quite small in this energy range. In addition, the consensus opinion is that the dominant process is radiative decay of the Δ produced incoherently from ^{12}C. This assumption is also the basis of the MiniBooNE estimate of the NC γ background to oscillations. The cross sections from three recent theoretical calculations are compared to three neutrino event generators in Fig. 3.

The MiniBooNE estimate comes from the NUANCE event generator[25], scaled to the Mini-

BooNE measurement of the NCπ^0 channel. This method calibrates the NC Δ production. Note the good agreement between the model calculations and the MiniBooNE estimate (NUANCE). In short, the most recent theory consensus is that the MiniBooNE estimate of NCγ is correct. To explain the MiniBooNE neutrino excess with NCγ production would require that that current MiniBooNE estimate is incorrect by a factor of 2-3. The most recent calculations as shown in Fig. 3 show that is unlikely.

However, the excess occurs in the low-energy where the NC π^0 and NC Δ radiative decays ($\Delta \rightarrow N\gamma$) backgrounds are the largest. Current theory consensus notwithstanding, a careful check of both of these backgrounds is important. We are proposing to measure these NC backgrounds with a new technique combined with additional running of MiniBooNE.

The MiniBooNE detector uses 800 tons of mineral oil (CH_2) as a target medium for inducing CC and NC neutrino interactions. The mineral oil also serves as the detector medium for observing the final state particles resulting from the interactions. This is achieved via detection of the Cerenkov light from charged particles in the 1280 8" photomultiplier tubes (PMTs) that line the inside of the spherical detector tank. In addition to the Cerenkov light produced in a cone around the trajectory of charged particles, some isotropic scintillation light is produced due to presence of aromatic impurities in the mineral oil.

We propose adding approximately 300 kg of PPO scintillator to the 800 tons of MiniBooNE mineral oil to increase the amount of scintillation light produced by 2.2 MeV γ that result from delayed ($\tau \approx 186$ μs) neutron capture on protons within the mineral oil. This will allow an important test of the oscillation signal by checking that the excess is indeed due to CC interactions of low-energy neutrinos and not an incorrectly calculated NC background. This can be done by counting n-capture events that follow oscillation candidate events. If the excess is indeed due to CC interactions of low energy ν_e, only approximately 10% of the excess will have associated n-capture events. If, instead, the excess is due to a NC process, one would expect many more neutrons produced since the interactions are caused from higher energy neutrinos. One expects approximately 50% of NC background events to have an associated neutron. An attractive feature of this method is that the neutron fraction for CC and NC processes may be measured with MiniBooNE via similar channels thereby eliminating that systematic uncertainty.

The increased level of scintillation will enable several other important measurements. The detection of n-capture enables a measurement of the neutron to proton ratio in NC elastic scattering which is sensitive to the strange-quark spin of the nucleon (Δs). The β decay from the $^{12}N_{\text{g.s.}}$ in the ν_μ $^{12}C \rightarrow \mu^-$ $^{12}N_{\text{g.s.}}$ process will be better reconstructed which will allow a measurement of this process and a check of the low-energy neutrino flux. Low-energy recoil nucleons will be more visible within neutrino events allowing a test of the quasielastic assumption in neutrino energy reconstruction.

In the following sections, we describe the extended physics program that is made possible with the addition of scintillator to MiniBooNE. We will discuss how the scintillation light will be increased, how it affects event reconstruction, and describe a plan for future running with MiniBooNE in this new configuration.

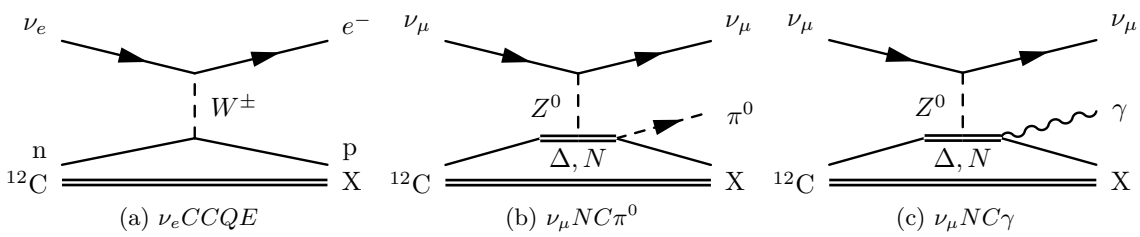
3 Physics goals

The main motivation for adding scintillator to MiniBooNE is to provide a test of the nature of the low-energy excess of events observed in both the ν_e and $\bar{\nu}_e$ appearance searches conducted by MiniBooNE. The addition of scintillator will also enable an investigation of the strange-quark contribution to the nucleon spin (Δs), a measurement of the $\nu_\mu\ {}^{12}C \rightarrow \mu^-\ {}^{12}N$ reaction, and a test of the quasielastic assumption in neutrino energy reconstruction.

3.1 Oscillation search with CC/NC identification

MiniBooNE has measured a 3.8σ excess of oscillation candidate events in the combined ν_μ and $\bar{\nu}_\mu$ data sets collected to date at Fermilab [6]. As can be seen in Fig. 1, the predicted backgrounds in the low energy regions, where the excess is most substantial, are dominated by neutral current backgrounds. These are from two major sources, both from NC interactions: misidentification of the π^0 ("π^0 misid") and the production of Δ baryons which then radiatively decay ("$\Delta \rightarrow N\gamma$"). A test of these NC backgrounds in a measurement with different systematic errors would be quite valuable to firmly establish the oscillation excess.

MiniBooNE can perform this test by detecting neutrons associated with oscillation candidate events. At low E_ν^{QE}, in true CCQE oscillation events (Fig. 4a), a proton is produced and neutrons are only produced via final state interactions within the carbon. This effect is expected to produce neutrons in less that 10% of CCQE oscillation events. The NC backgrounds, on the other hand, (Figs. 4b,4c) should contain neutrons in $\approx 50\%$ of the events due to the dominance of the Δ in these processes, which decays to a neutron $\approx 50\%$ of the time.



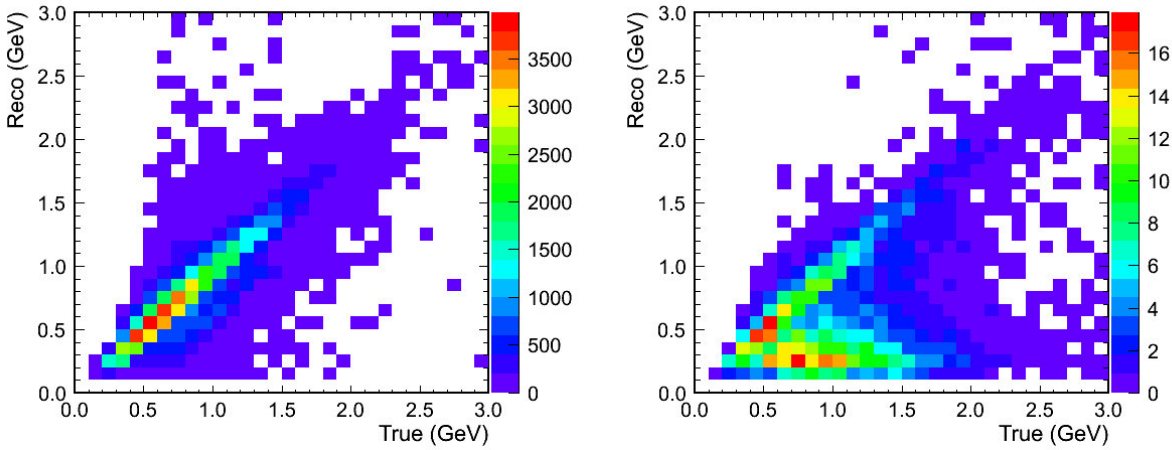
(a) $\nu_e CCQE$ (b) $\nu_\mu NC\pi^0$ (c) $\nu_\mu NC\gamma$

Figure 4: Diagrams of signal (a) and background (b,c) neutrino oscillation candidate events.

Note that E_ν^{QE} is the reconstructed neutrino energy using the assumption of neutrino quasielastic scattering from a neutron. This quantity should be a good estimate for the actual neutrino energy in true CC oscillation events (excepting possible nuclear effects, Sec. 3.4). However, because of the large missing energy in NC events, the actual neutrino energy is, higher than E_ν^{QE} for a large part of the NC background events as can be seen in Figure 5. Note the large number of events reconstructed at low energies feeding down from higher energy. These are mainly the NC background events that "pile up" in the lower E_ν^{QE} region.

So, the NC backgrounds will contain more final state neutrons because the events are produced via the Δ *and* because these events are from higher-energy neutrinos where more energy is deposited in the nucleus. More detailed explanations and simulation results are presented in Section 5.

In practice, we would rerun the MiniBooNE oscillation search in neutrino mode after the addition of scintillator in order to enable neutron detection. Oscillation candidates would be selected with the same strategy as the original search. From this sample, we would search for neutron capture events and measure the neutron fraction which would test the NC background estimates. An important feature of this measurement is that the neutron fraction may be "calibrated" for the oscillation search via MiniBooNE+ ν_μ CCQE and ν_μ NCπ^0 measurements which greatly reduces



(a) ν_e signal events

(b) background events

Figure 5: Reconstructed E_ν vs. true E_ν for simulated MiniBooNE candidate oscillation events.

errors from any nuclear model uncertainties. A quantitative study that includes a more complete nuclear physics model, estimates of final-state interactions, detector efficiency, and an estimate of sensitivity is presented in Section 5.

3.2 Δs from the proton to neutron ratio in NC elastic events

The NC neutrino-nucleon elastic scattering (NC elastic) interaction, $\nu N \to \nu N$, is sensitive to the isoscalar-axial structure of the nucleon [26], so will be sensitive to the effects of strange-quark contributions to the nucleon spin (Δs) and may contribute substantially to the nucleon spin puzzle, an area of continued interest and effort (e.g. [27]). A measurement of this process with sufficient sensitivity has not yet been realized.

MiniBooNE has made the most accurate measurement to date of the differential cross section for both the $\nu N \to \nu N$ [28] and $\bar{\nu} N \to \bar{\nu} N$ [29] processes with event samples of several $\times$10k. While these are valuable measurements to help with understanding of neutrino-nucleon scattering, they are not sensitive to Δs because the acceptance of MiniBooNE is approximately equal for neutrons and protons. The $\nu p \to \nu p$ process is sensitive to Δs with the opposite sign as $\nu n \to \nu n$ and any strange quark effects cancel in the existing MiniBooNE measurement.

This situation changes abruptly with the addition of neutron-capture tagging. In that case, the neutrons and protons can be separately identified and the neutron/proton ratio,

$$R(p/n) = \frac{\sigma(\nu p \to \nu p)}{\sigma(\nu n \to \nu n)}, \tag{1}$$

is quite sensitive to Δs [26]. Based on previous studies [30], a rough estimate is that a 10% measurement of $R(p/n)$ should result in an error of ≈ 0.05 uncertainty on Δs. It should be realized that the recent results from MiniBooNE on the unexpectedly large CCQE cross section [31] may call into question the theoretical uncertainty involved in extracting Δs from $R(p/n)$. If there are multinucleon correlations contributing substantially to NC elastic scattering, it may not be clear how that affects the extraction of Δs. Regardless, a 10% measurement of $R(p/n)$ will be a valuable constraint and will spur more theoretical investigation.

Results from a Monte Carlo study of a $R(p/n)$ measurement with MiniBooNE+ are presented in Section 6.

3.3 A measurement of $\nu_\mu\ ^{12}C \rightarrow \mu^-\ ^{12}N_{\mathbf{g.s.}}$

The reaction $\nu_\mu\ ^{12}C \rightarrow \mu^-\ ^{12}N_{\text{g.s.}}$ is an interesting reaction to study with a scintillator-enhanced MiniBooNE for several reasons. It comes with a distinctive tag from the β-decay of the $^{12}N_{\text{g.s.}}$ with endpoint energy of 16.3 MeV and lifetime of 15.9 ms. This addition of scintillator to MiniBooNE will allow for high efficiency and better reconstruction of the β-decay. Since it is an exclusive reaction, the theoretical cross section can be calculated to $\approx 2\%$ very near threshold [32]. It was measured by LSND for both ν_μ and ν_e [32, 33] and by KARMEN for ν_e [34] to agree with theory to within experimental errors. A measurement by MiniBooNE of this theoretically well-known reaction would enable a test of the low-energy neutrino flux which could better constrain the low-energy oscillation excess.

The event signature is quite distinct. The low-energy prompt μ^- and subsequent decay e^- would be detected with the usual techniques employed for ν_μ CCQE events combined with a requirement for a detected β-decay candidate. With the addition of scintillator to make 2.2 MeV γ visible, the efficiency for detecting the 16.3 MeV-endpoint β will be quite high.

The challenge is that the fraction of the total ν_μ scattering events that interact via $\nu_\mu\ ^{12}C \rightarrow \mu^-\ ^{12}N_{\text{g.s.}}$ is small. In the lowest energy bin at $E_\nu \approx 250$ MeV, the cross section is about 4% of the ν_μ CCQE cross section, falling to about 0.5% by $E_\nu \approx 400$ MeV [35]. However, with the data sample proposed here the total ν_μ event sample will be large, the $^{12}N_{\text{g.s.}}$ signature quite distinct, and an analysis will be worth the effort.

3.4 A test of the QE assumption in neutrino energy reconstruction

MiniBooNE has reported absolutely normalized cross sections for various ν_μ-carbon processes including ν_μ CCQE [31], CCπ^+ [36], CCπ^0 [37], NC elastic [28], and NCπ^0 [38]. They all show a 30-40% larger cross section than predicted in previously existing models (e.g. [39]). One emerging idea is that two-nucleon correlations in carbon are contributing significantly to the interaction cross section [40, 41]. If this is the correct explanation for the extra strength in these neutrino interactions, then it could also have a significant effect on the reconstructed neutrino energy in oscillation events, E_ν^{QE}, which assumes quasielastic scattering from single nucleons within carbon [42]. In short, the reconstructed neutrino energy may be incorrect in a large fraction of the oscillation events leading to incorrect conclusions about the resulting fits to oscillation models.

The addition of scintillator will allow this idea to be experimentally tested. With the scintillator addition proposed here, the detector response to final state nucleons in a typical CCQE event will be increased by about a factor of five. This scintillation light is a measure of the total energy in the event (E_ν^{total}) as opposed to that reconstructed from just the lepton track, E_ν^{QE}. A comparison of E_ν^{QE} with E_ν^{total} will allow further insight into the two-nucleon correlation issue in general and, specifically, into its relevance to the low-energy oscillation excess.

4 Increasing scintillation for MiniBooNE+

In order to execute the main goal of a NC/CC test of the oscillation excess, the detector light output response to neutron captures in MiniBooNE must be increased. This can be accomplished by adding a few hundred parts per million of a scintillator such as butyl-PBD or PPO to the MiniBooNE mineral oil. The resulting level of scintillation will provide a distinct signature of neutron capture.

This technique was demonstrated and used by the LSND experiment [43] to search for $\bar{\nu}_e$ appearance oscillations via inverse β-decay with coincident neutron signal. Initial investigations of this were conducted using the same scintillator as LSND, butyl-PBD. However, about midway through this work, a less expensive alternative, PPO, was identified. PPO is being used in the NOvA experiment, can be obtained from the same supplier for a price of about 1/4 that of butyl-PBD, and has very similar scintillation characteristics. In this section, we report on investigations of both these candidate scintillators, but have now decided to use PPO.

When a fast neutron of up to a few hundred MeV is produced by a neutrino interaction in mineral oil (CH_2), it rapidly loses energy by elastic and inelastic collisions with the mineral oil until it is reduced to thermal energies (i.e. "thermalizes"). This thermal neutron will capture on hydrogen 99.5% of the time and on carbon the remaining times with a total characteristic lifetime of 186 μs for mineral oil. The hydrogen capture ($np \rightarrow d\gamma$) yields a 2.2 MeV γ, while the ^{12}C capture emits a 5 MeV γ.

In addition to allowing for neutron identification (i.e. "n-tagging"), increasing the scintillation light in MiniBooNE will also allow for better sensitivity to the sub-Cerenkov threshold events (e.g. nucleons) in addition to the super-Cerenkov leptons.

4.1 Neutron capture

By measuring the energy, position, and time of the event, a selection criteria can be formed which will select n-capture events that are correlated with the primary neutrino event with high efficiency yet reject accidental events. The LSND experiment used the n-capture technique to select $\bar{\nu}_e p \rightarrow e^+ n$ events via detection of the prompt e^+ signal in coincidence with the delayed 2.2 MeV photon from neutron capture. A neutron likelihood can be formed with the PMT hit multiplicity, prompt-delayed capture distance, and timing distribution, and it was able to achieve a 51% detection efficiency for correlated n-capture events while only being susceptible to a 1.2% accidental probability.

The average PMT multiplicity from a 2.2 MeV γ was 35 PMT hits in the LSND experiment. As MiniBooNE and LSND are comparably sized detectors with similar readout PMTs, the same efficiency and accidental rate suppression can be achieved by raising the MiniBooNE scintillation to yield the same PMT multiplicity for 2.2 MeV γ. LSND, with 25% photocathode coverage, was able to achieve this light yield with 30 mg of butyl-PBD per liter of mineral oil. MiniBooNE has an 11% photocathode coverage, and this requires a higher amount of scintillator to achieve similar performance.

4.2 Scintillation light in MiniBooNE, currently

Sub-Cerenkov-threshold particles can produce some light in the current MiniBooNE configuration with "pure" mineral oil. This occurs because of aromatic benzene-like impurities in the MiniBooNE mineral oil, and the light output from these has been characterized in a variety of benchtop and in-situ tests [44, 45, 46]. The various tests are in reasonable agreement and have enabled the

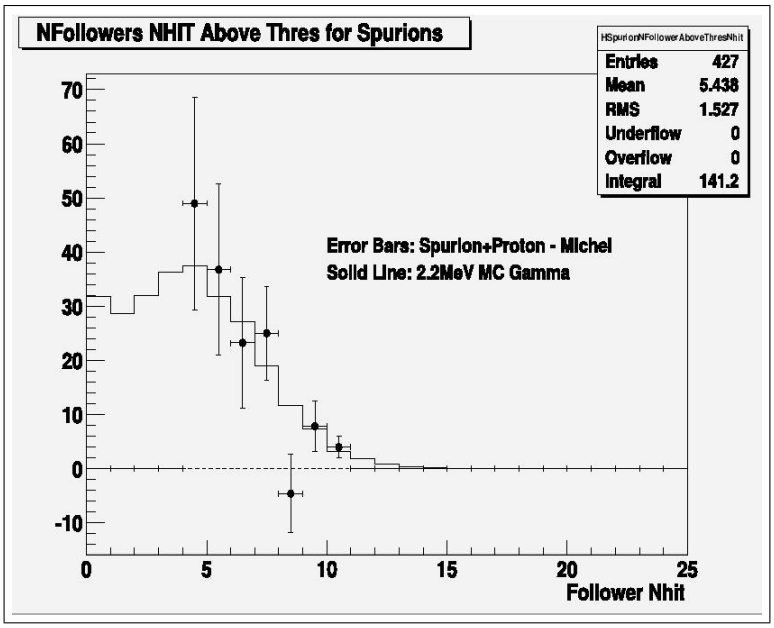


Figure 6: PMT multiplicity distribution from neutron-capture candidate events in an 2004 data study [47]. The data points are shown with error bars after subtraction of random coincidence rate. There is no data below 4 hits because of the trigger threshold. The MC prediction is shown as solid histogram. "Spurion" was a whimsical name given to neutron-capture candidates.

scintillation and related fluorescence to be characterized and coded into the MiniBooNE detector Monte Carlo (MC) simulation of the optical model. The main result that can be used to benchmark the well-characterized MiniBooNE oil is that it has a scintillation strength of 32 visible photons emitted per MeV of energy deposit at a wavelength peak of 350 nm, with width $\sigma = 25$ nm, and a decay time of 34 ns [46].

The results of these scintillation tests have been folded into a complete, optical-photon model that accounts for absorption, re-emission, and various scattering processes, and well-describes the MiniBooNE data. The optical-photon model has been used to predict the current MiniBooNE response (undoped with additional scintillators) to 2.2 MeV γ, and it predicts a multiplicity of approximately 5 PMT hits with about 80% of the light in the directed Cerenkov cone. The remaining 20% of light is due to both isotropic scintillation and the isotropic re-emission of scattered UV Cerenkov light. These results have been verified in a study with MiniBooNE data in 2004 [47] to determine the feasibility of adding a neutron-capture trigger at that time. Figure 6 shows the PMT multiplicity distribution for neutron-capture candidate events ("follower" events) derived from this study. This shows that the MC correctly simulates the current level of scintillation and response to 2.2 MeV n-capture events, and that the response is too low to conduct a neutron search with the current scintillation level (nominally undoped, less the fluorescent impurities).

4.3 Estimate of the accidental neutron rate from MiniBooNE data

In initial calculations form MiniBooNE+, we have assumed that the probability for an accidental coincidence between a primary neutrino event and a subsequent 2.2 MeV capture photon will be the same as that for LSND, approximately 2%. The rate for MiniBooNE+, after adding scintillator, should be about the same as the overburden and energy thresholds are similar, however, we checked our assumption by measuring the accidental rate in current MiniBooNE data. It is a fairly rough

test because 2.2 MeV photons, with only ≈ 6 PMT hits (Fig. 6) are not well-reconstructed in MiniBooNE, but it is an important number as it determines the efficiency and purity for finding true n-capture events.

In this analysis, random snapshot ("strobe") data was selected to find events consistent with 2.2 MeV photons. The hits within a particular event were required to have an r.m.s. time spread of 15 ns and the charge-weighted average position was calculated. The resulting "accidental gamma" rate per unit volume averaged over the fiducial volume of the MiniBooNE detector was determined to be 0.5 events/s/m^3. An estimation of the efficiency difference after the addition of scintillator (mainly due to energy threshold) requires that rate to be scaled by a factor of 8 for MiniBooNE+. That results in an estimated n-capture accidental rate of 4 events/s/m^3, quite comparible to that measured by LSND of 4.3 events/s/m^3 [43], and consistent with the accidental n-capture probability assumed in this document.

4.4 Simulations of increased scintillation light

We first assess how much light must be produced by a given scintillator before determining the amount of scintillator required. Using the MiniBooNE detector MC, the total scintillation fraction can be increased, and the PMT multiplicity simulated for 2.2 MeV n-capture γ. As the scintillation level is increased by a scaling factor k, the total isotropic response (light not in the prompt, directed Cerenkov light cone) increases faster than k because the scintillator absorbs Cerenkov light in the UV (not detected by the PMTs) and shifts it into the PMT wavelength sensitivity range. This additional contribution is isotropically re-emitted and is then detected by the PMTs.

Initial light output tests were performed with a naive scintillation model by scaling the 350 nm light emitted by the current fluors present in the MiniBooNE oil. A more sophisticated model was developed that utilized a fluor model more appropriate for a PPO-type scintillator, as shown with the PMT quantum efficiency (QE) in Fig. 7. A fluor such as PPO is more efficient at increasing the scintillation compared to the current fluors in the MiniBooNE oil because the emission spectrum has a longer average wavelength for which the attenuation length of the mineral oil is longer and the PMT QE is higher. Also, a PPO-type has comparable fast and slow scintillation components (2 ns and 20 ns, respectively) in contrast to the current MiniBooNE fluors which contain just a slow component (34 ns). The fast scintillation component significantly improves the reconstruction of the n-capture position reconstruction as will be seen below in Sec. 4.5.

The results from the MC studies are summarized in Fig. 8. Note that the efficiency for finding events over threshold (PMT multiplicity) of 10 hits increases with the scintillation multiplier as does the average PMT multiplicity. A scintillation multiplier of 1 represents no additional scintillation beyond that of the current MiniBooNE fluors in mineral oil (32 photons / MeV). Also note that the PPO model with a scintillation multiplier of 15 is equivalent to the naive model at about a value of 22 because PPO has a more optimal overlap of its emission spectrum with the PMT QE and there is a longer attenuation length of mineral oil at these wavelengths. The detection efficiency and PMT multiplicity results for PPO lead to the conclusion that a multiplication factor of 15 times the current MiniBooNE value is sufficient to reconstruct the 2.2 MeV n-capture γ.

4.5 Event reconstruction

Based on the MC studies of increased scintillation light in n-capture events, an increase of the scintillation strength by a factor of 15 with PPO should be adequate. Further studies were performed using the existing MiniBooNE reconstruction apparatus to determine how well 2.2 MeV γ and higher energy electrons are reconstructed with their increased scintillation light.

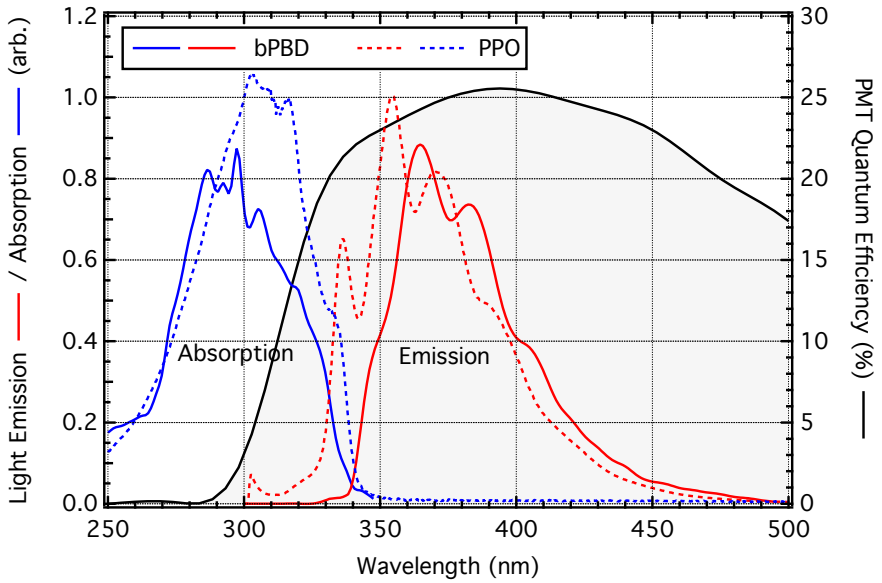


Figure 7: The absorption and emission spectra of butyl-PBD and PPO with the MiniBooNE PMT quantum efficiency overlaid on the right.

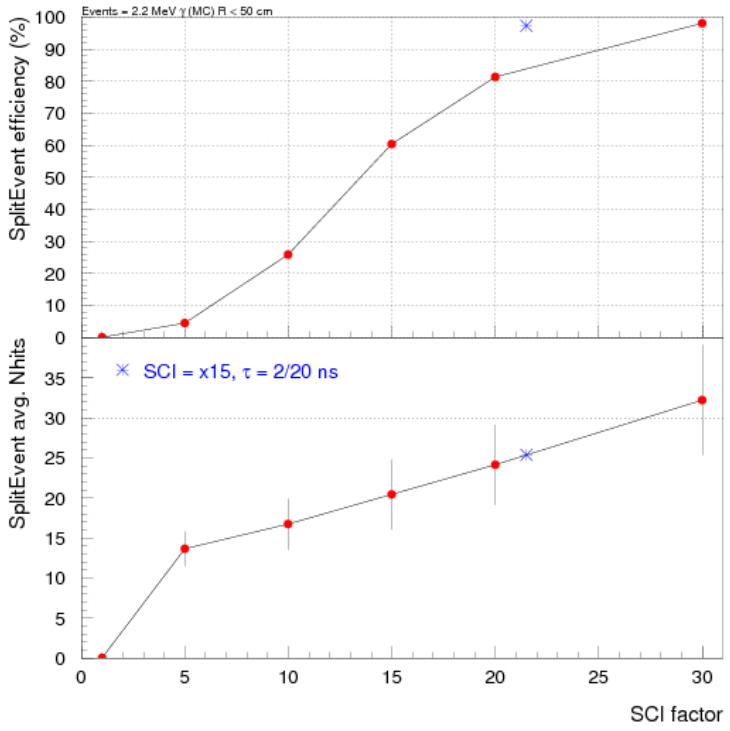


Figure 8: Neutron capture (2.2 MeV γ) event detection efficiency (top) and the average PMT multiplicity distribution (bottom) is shown as a function of scintillation strength multiplier (SCI factor). The red points are from the naive scintillation model where the current 350 nm MiniBooNE mineral oil emission is scaled from current value. The blue point is for the PPO model at scintillation strength of 15 times the current MiniBooNE mineral oil and with light output equivalent to the naive scintillation model with a strength multiplier of about 22.

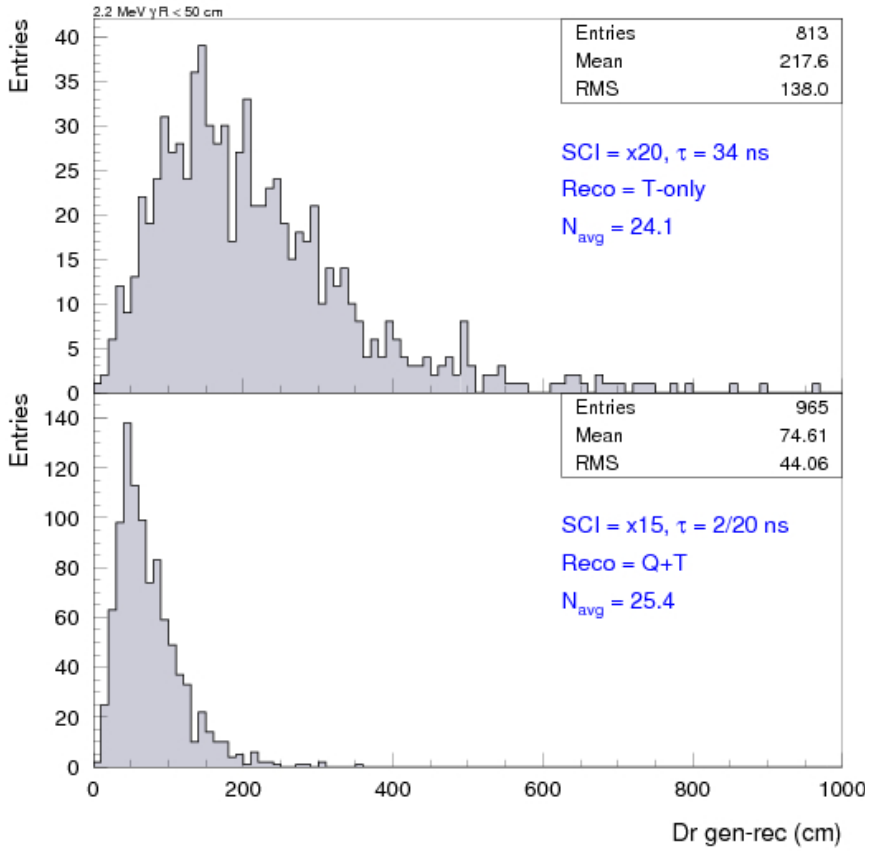


Figure 9: Position resolution of simulated 2.2 MeV γ events for the naive scintillation model (top) compared to that for $\times 15$ scintillation (bottom).

Low-energy events such as 2.2 MeV γ are reconstructed using PMT charge and time information. For position reconstruction, the time information is the most critical as the time of arrival at each tube allows the position to be determined. It is crucial to have a scintillator with a fast time component or the position information is degraded. This is especially true with low-light events where the PMTs are typically detecting an average of one photoelectron. These effects can be seen in Fig. 9 where the position resolution for 2.2 MeV γ is plotted for both the naive and PPO scintillation models, using new reconstruction algorithms developed specifically for this task. The PPO model with a fast scintillation component of 2 ns results in improved position reconstruction of $\approx$75 cm. This is comparable to that achieved in the LSND n-capture reconstruction and, therefore, should yield similar n-capture efficiency and accidental background rejection.

Adequate reconstruction of n-capture events is only part of the reconstruction battle. This increased level of scintillation light must not degrade the electron reconstruction which is crucial for an oscillation analysis. This was studied by generating electron events using the detector MC with the PPO scintillation model and then reconstructing these events using the current MiniBooNE algorithms. This was first tested with 50 MeV electrons. The Cerenkov cone is still readily located within the increased scintillation light as can be seen in Fig. 10 where the angular distribution of the light around the reconstructed electron direction is plotted. The level of isotropic light is increased by about a factor of 15 as expected, but the higher level of directed light in the Cerenkov cone is still quite obvious.

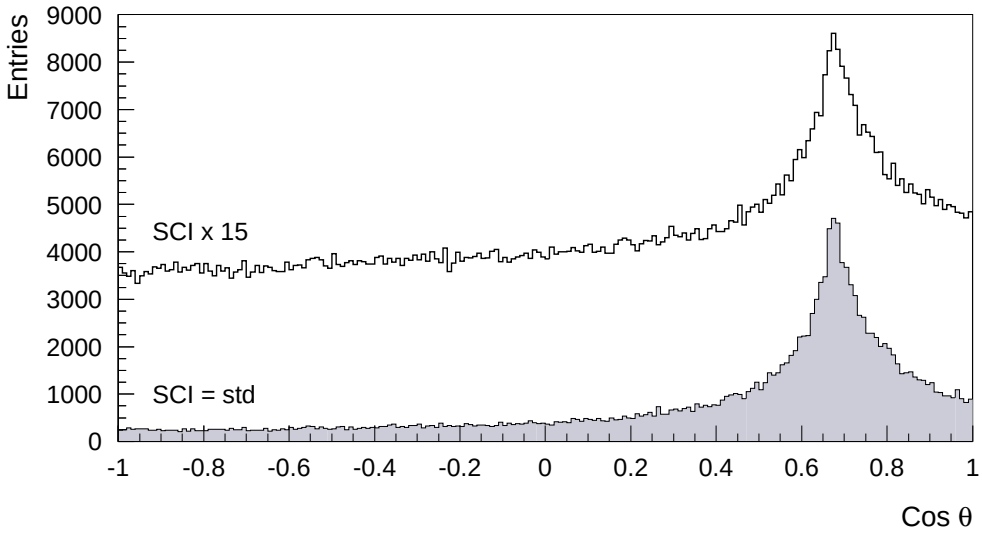


Figure 10: Angular distribution of light around the reconstructed direction of 50 MeV electrons for the standard (current) scintillation model compared to $\times 15$ scintillation.

The reconstruction of higher energy electrons has also been studied. In order to obtain the optimum reconstruction of neutrino events, the PMT charge and time likelihoods will need to be redetermined for the new scintillator mixtures.

MiniBooNE has several levels of reconstruction, the first "SFitter" assumes a point like model for the lepton track. The second "RFitter" contains an extended track model [48] and was used for the particle identification (PID) in the main oscillation analysis but is very sensitive to tuning which has not yet been performed. The SFitter has a more complex PID algorithm but is less sensitive to tuning. Results from applying these reconstruction algorithms to the simulated 100-600 MeV electrons are shown in Fig. 11. The SFitter and RFitter results are shown with the standard (current) scintillation model. The SFitter was run with no modifications to the underlying likelihoods and then with only a minor adjustment to the energy scale. There are a few things to note in this plot. First, the untuned SFitter with increased scintillation returns degraded resolution values across the energy range. This is expected as the underlying parameters of the fit are incorrect in this case. However, the SFitter with minor modifications actually has better position resolution than the standard case. It approaches the standard value at higher energy for angular resolution. The performance of the untuned RFitter with increased scintillation is off the scale in Fig. 11.

The conclusions from these studies are that simple changes to the SFitter recover resolution to the standard level after a minor change to adjust for the stronger scintillation light. We expect to improve this for the SFitter with proper tuning of the time likelihoods and underlying optical model. From the behavior of the SFitter, we expect to recover the good resolution for the RFitter after the required retuning of the algorithm.

The results of these studies indicate that an increase of scintillation light with a PPO-type dopant by about a factor of 15 is sufficient for the desired n-capture reconstruction accuracy. In our studies of simulated data with increased scintillation light, good electron reconstruction is maintained up to ≈ 600 MeV. If electrons can be reconstructed sufficiently, we maintain that π^0 and μ will also be reconstructed with accuracy as in existing analyses and the particle identification performance required for the oscillation analysis will be achieved.

The reconstruction of nucleons is also an important component of the measurements described

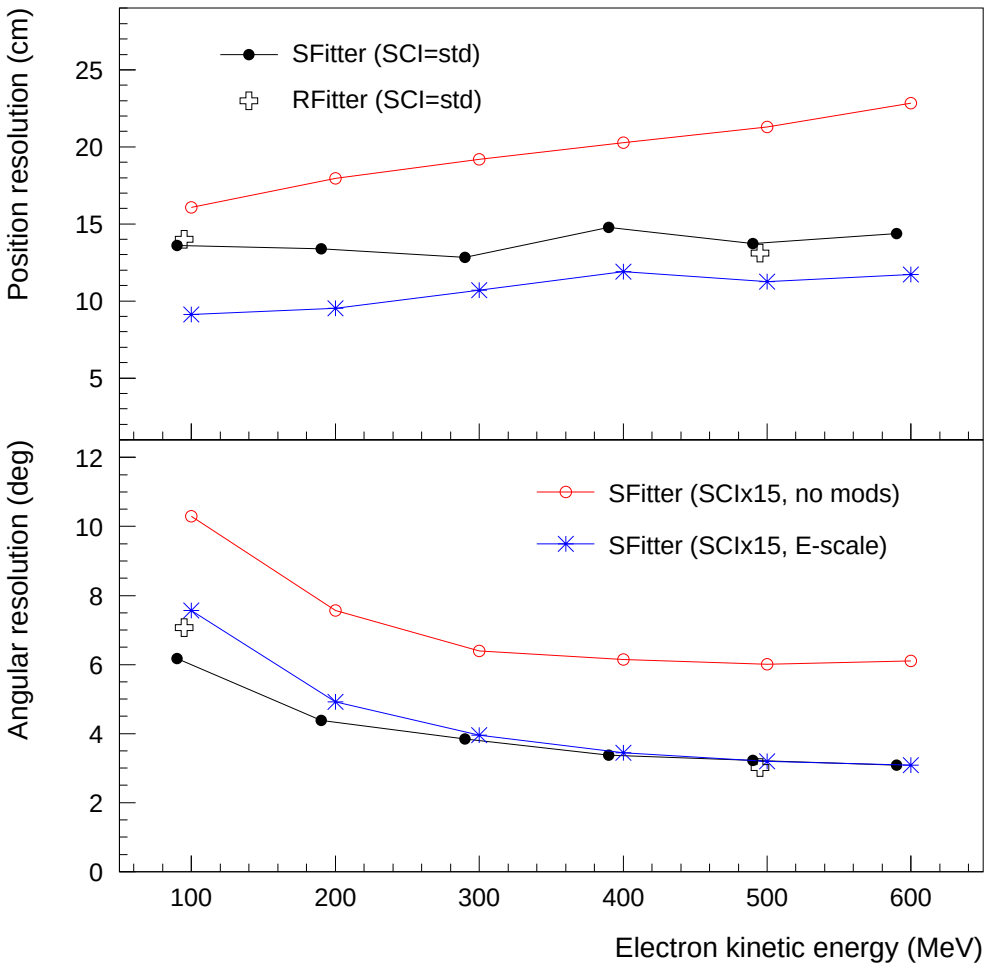


Figure 11: Position (top) and angular (bottom) resolution obtained with the MiniBooNE reconstruction "SFitter" and "RFitter" algorithms for 100-600 MeV electrons with both the standard (current) scintillation model and a $\times 15$ model. The Rfitter was run at only 100 and 500 MeV.

here, in particular for Δs and for the investigation of the QE assumption in neutrino energy reconstruction. A sample of NC elastic scatter events were run through the detector MC with both the standard scintillator model as well as the $\times 15$ model. The addition of scintillator helps the reconstruction of these events immensely. As shown in Fig. 12 and as would be expected, the amount of light from few-hundred MeV protons increases by more than order of magnitude. This will lower the systematic uncertainty on low energy nucleons by a large factor. The biggest improvement comes from the drop in efficiency (and associated uncertainty) at below 200 MeV due to small numbers of hits. Note that with the addition of scintillator that drop in efficiency is pushed down to 20 MeV. The energy resolution also decreases from 30% to 10% for 100 MeV protons with the addition of scintillator. These features will extend our physics reach to much lower proton energies.

4.6 Determination of the scintillator cocktail

From the studies in the preceding sections, we have determined that we should add an amount of scintillator with absorption/emission spectrum and lifetime of butyl-PBD or PPO to obtain a light

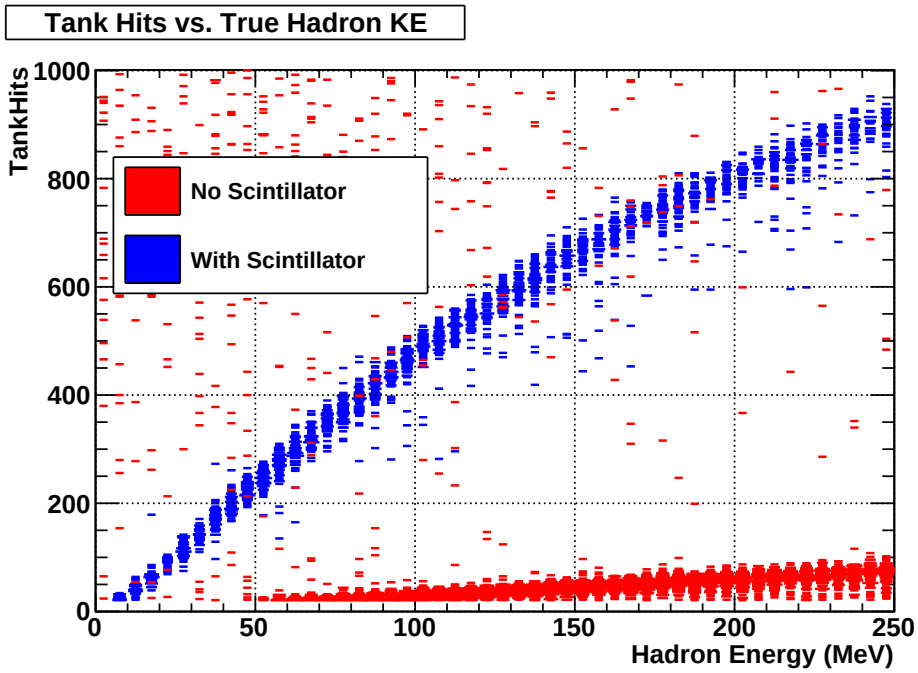


Figure 12: Distribution of PMT hits as function of proton energy in NC elastic scattering events for standard and ×15 scintillator.

yield of 15 times that the current level in MiniBooNE.

To determine the scintillator concentration that will produce this light level, we have examined data collected during MiniBooNE oil tests in 2001-2002 together with recent tests. In 2001-2002, the level of scintillation in candidate mineral oils for MiniBooNE was measured at the Indiana University Cyclotron Facility proton beam [49]. This beam was ideal for these tests as the 200 MeV proton beam is below the Cerenkov production threshold, and a direct measurement of the isotropic scintillation light could be isolated. While the tests focused on the scintillation from pure mineral oil, several scintillators were tested with the idea that a slight amount of scintillator could be beneficial for MiniBooNE particle identification. The tests with butyl-PBD are shown in Fig 13. In separate tests, it was determined that scintillation from pure MiniBooNE mineral oil produced 5 photoelectrons with the same experimental setup. Therefore, in order to produce a factor of 15 more light than pure MiniBooNE mineral oil (Sec. 4.4), approximately 0.3 g/l of butyl-PBD is desired. Similar tests of butyl-PBD were carried out in service of LSND [50] and are consistent with the MiniBooNE results.

In the process of considering butyl-PBD[1] as a candidate scintillator, PPO[2] was identified as another possibility. As can be seen in Fig. 7 the absorption / emission spectra are quite similar between butyl-PBD and PPO. In addition, the light output at a given concentration of PPO in mineral oil is about the same as butyl-PBD, and the characteristic emission times are about the same with a fast component around 2 ns [51]. The price of PPO is about 1/4 of the price per kg of butyl-PBD.

In order to investigate PPO further and to verify the old results on butyl-PBD, the test setup from the 2001-2002 IUCF tests was modified. Instead of operating in the 200 MeV proton beam,

[1]Butyl-PBD is a synonym for 2-(4-tert-Butylphenyl)-5-(4-biphenylyl)-1,3,4-oxadiazole, CAS Number 15082-28-7
[2]PPO is a synonym for 2,5-Diphenyloxazole, CAS Number 92-71-7

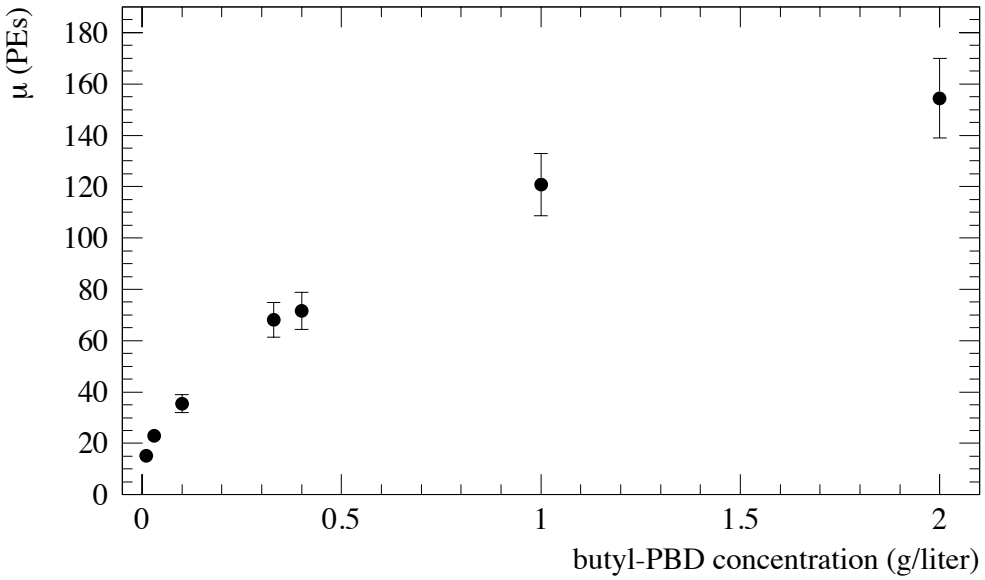


Figure 13: MiniBooNE tests on light level vs. concentration of butyl-PBD [49]. The vertical scale is number of photoelectrons (PE) produced with that particular apparatus.

the test setup utilized a strong, collimated ^{60}Co γ source with the original oil test apparatus. The light output of various concentrations of butyl-PBD and PPO in mineral oil were tested, and the results are shown in Fig. 14. From these tests it was determined that the light output from butyl-PBD and PPO at a given concentration are the same. The data from 2001-2002 IUCF tests [49] on butyl-PBD are overlaid on the plot with an arbitrary matching of scale as the light collection efficiency in the current setup is not absolutely calibrated. However, the behavior with scintillator concentration is the same between the different tests. If the old data is used to set the scale, then our current tests indicate that PPO has the same light output as butyl-PPD and a concentration of 0.3 g/l of PPO will yield a factor of 15 light increase in the MiniBooNE mineral oil.

4.7 Solubilty and detector material compatibility with PPO

The solubility of many scintillators is quite poor in mineral oil. We performed laboratory tests to determine the limit of both PPO and butyl-PBD solubility. Butyl-PBD was found to have poor solubility. With extensive agitation at slightly elevated temperatures, a maximum solubility of 2 g/L was demonstrated. A 2.5 g/L sample was agitated at an elevated temperature for over a month and this concentration of bPBD was not found to completely dissolve. In contrast, PPO exhibited markedly improved solubility and was found to be about 45 g/L at room temperature. An additional test was performed where 5 g/L of PPO was dumped into mineral oil, and the mixture was not agitated. In this way, we found that natural, diffusive currents in the mineral oil was sufficient to fully dissolve PPO, albeit on a 2-week time scale. The maximum solubility ensures that the entire 300 kg of PPO that we are proposing to use can be mixed entirely within the 10,000 L overflow reservoir.

We also performed material compatibility tests with components from inside the MiniBooNE detector in a PPO sample. Aluminum samples with the primer, black paint, and white paint used inside of MiniBooNE were soaked in a 20 g/L sample of scintillator. This sample is over 50 times the concentration that is proposed for MiniBooNE. We also soaked samples of the coaxial cables

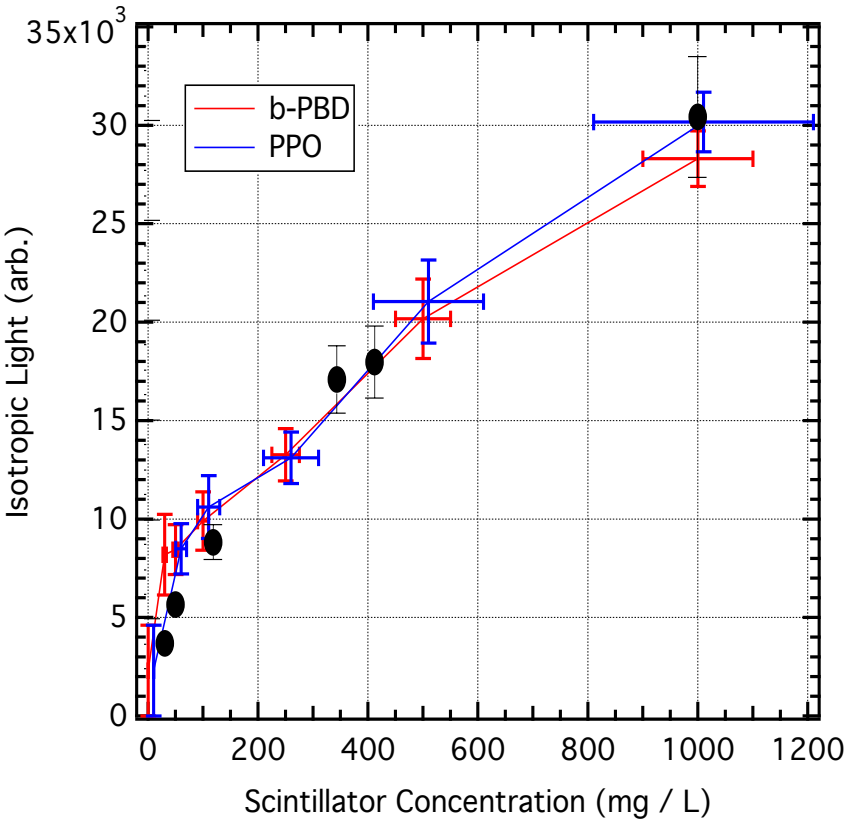


Figure 14: Recent tests of isotropic light output from butyl-PBD and PPO in mineral oil as a function of scintillator concentration. The recent lab tests are shown as red and blue points. The data taken from early mineral oil tests with butyl-PBD [49] are shown as black points and are overlaid.

and black Master Bond EP21LV encapsulant used on the MiniBooNE PMTs in the scintillator sample. Another set of these samples was placed in a pure mineral oil sample as our control. After more than 5 months there was no discernible change in the material samples in the PPO and the samples in the mineral oil. It seems that PPO has no additional effect on the MiniBooNE materials that the pure mineral oil already has. In this case, these materials have been "soaking" in pure mineral oil for over a decade. Another set of the same materials were also placed in a 17 g/L PPO sample and agitated for over 7 months. Again, no visual or mechanical differences were observed when compared to unexposed materials.

E_{QE}(GeV)	[0.2 , 0.3]	[0.3 , 0.475]	[0.475 , 1.25]
coh	1.5 (2.9)	6.0 (9.2)	2.1 (8.0)
inc	12.8 (14.1)	27.7 (31.1)	14.4 (23.2)
inc(n)	5.2 (5.9)	12.5 (14.3)	6.4 (10.9)
H	4.1 (4.4)	10.6 (11.6)	4.6 (6.3)
Total	17.6 (21.4)	42.1 (51.9)	19.3 (37.5)
n/tot	0.30 (0.28)	0.30 (0.28)	0.33 (0.30)
MiniBN	19.5	47.3	19.4
Excess	42.6 ± 25.3	82.2 ± 23.3	21.5 ± 34.9

Table 1: Summary of predicted NCγ events for the MiniBooNE neutrino result in 3 bins for E_ν^{QE}. The rows are broken into coherent, incoherent, incoherent with neutron, and free proton contributions. The provide the total background prediction, an expected fraction of neutrons, comparison with the MiniBooNE prediction and excess. The numbers in () are excursions to estimate model uncertainty. This is an extension of the work in Ref. [21].

5 Oscillation sensitivity

In this section we explain the oscillation search strategy that will be employed using the enhanced scintillation light with MiniBooNE+.

5.1 Neutrons in oscillation signal and background events

As explained schematically in Sec. 3, enabling n-capture detection in oscillation events allows for additional discrimination between CC oscillation signal events and NC background events. Roughly, the fraction of NC background events should contain neutrons 50% of the time because of the dominance of the Δ resonance in these events. However, there are other diagrams that modify this simple assumption. Additionally, there are final state effects in the nucleus as well as detector effects that change these simple arguments.

5.1.1 Neutron fraction in NC background events

A more complete estimate of neutrons in NCγ events was provided by X. Zhang, one of the authors of Ref. [21], which provided an estimate of the NCγ background to the MiniBooNE oscillation using their effective field theory model for neutrino-nucleon, neutrino-nucleus interactions. These numbers are shown in Table 1. Note that their estimate for total NCγ background is very similar to the MiniBooNE estimate. This is consistent to the statements concerning Fig. 3 above. The other number of note in this table is the neutron fraction which is predicted to be 0.3. This can be understood in that the incoherent channel on carbon is the only one producing neutrons (via the Δ), the coherent and free proton contributions do not yield neutrons in final state. This effect, if the only additional complication, would lessen the discrimination of NC background events from CC signal. However, the effective detection efficiency counters this effect somewhat.

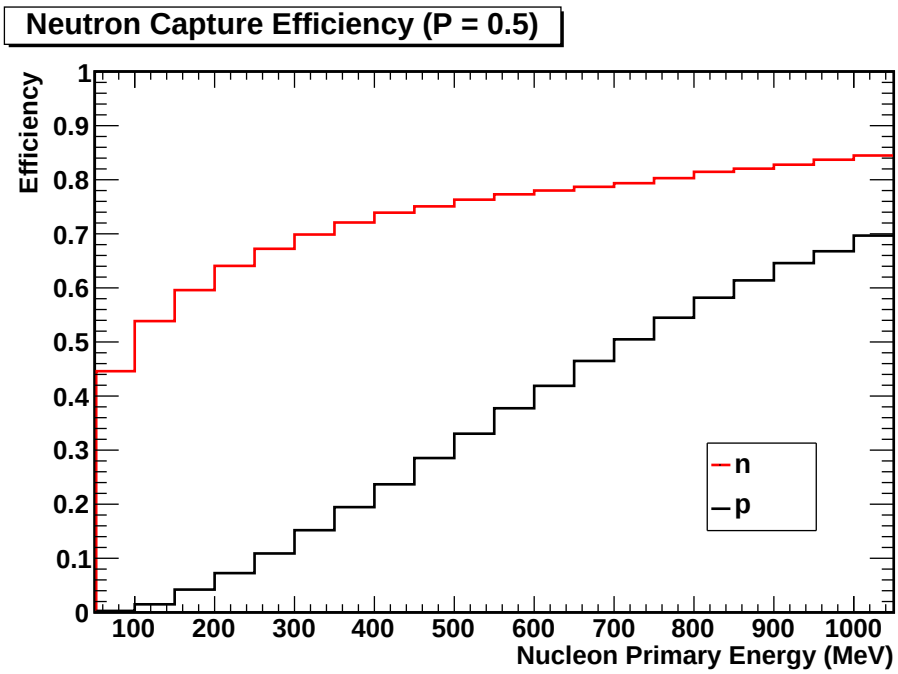


Figure 15: Effective efficiency for detecting 1 or more n-capture events as function of primary neutron and proton kinetic energy. A detection efficiency of 0.5 for each n-capture event is convoluted with an MCNP [53] calculation that simulates nucleon transport through the MiniBooNE mineral oil accounting for multiple neutron production.

5.1.2 Effective neutron detection efficiency

Neutrons (and protons, although less-so) traveling through the CH_2 detector medium have a probability to inelastically scatter with carbon and to knock out additional neutrons. This has the effect of increasing our estimated single n-capture capture efficiency in a calculable way. For this study we used the MCNP simulation [53] package as it is better-known to transport accurately nucleons of these energies. The resulting effective efficiency for the detection of a neutron as a function of nucleon kinetic energy is shown in Fig. 15. This is then combined with the NUANCE simulation described below to calculate n-capture efficiency for events given their final state nucleon energies. The trend of larger effective efficiency at higher nucleon energies serves to enhance the NCγ background separation as these nucleons tend to be of higher energy compared to CC signal events.

5.1.3 NUANCE simulation of oscillation signal and background events

The NUANCE neutrino event generator [25] has been tuned extensively by MiniBooNE to reproduce measured data and predict related backgrounds. The MiniBooNE neutrino oscillation signal and background data sets, generated with NUANCE were used to provide a detailed (and hopefully accurate) estimate of associated neutrons. The number of produced neutrons in the NUANCE samples agreed reasonably well with the predictions in Table 1 for both the NCγ channel as well as for the NCπ^0 channels which should have similar behavior for neutrons. The effective neutron detection efficiency was then applied to determine the background reduction with a neutron capture veto requirement. The end result of the lower neutron fraction combined with the larger effective

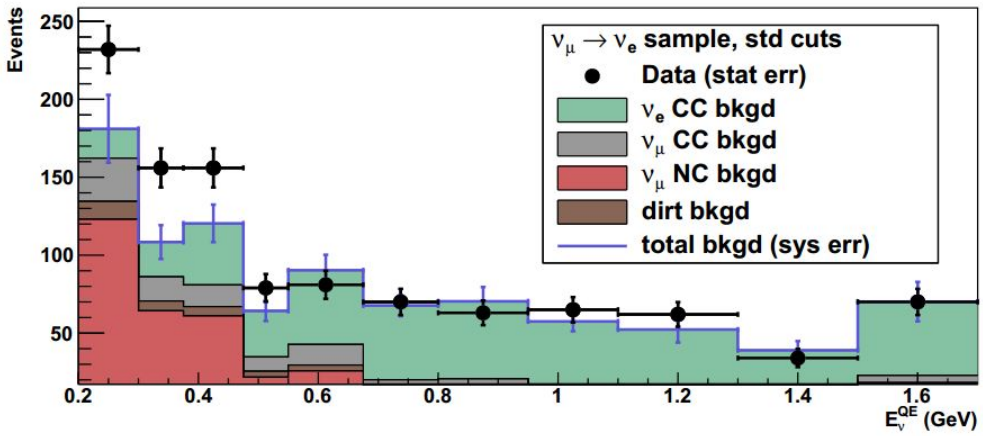


Figure 16: E_ν^{QE} distribution of the MiniBooNE neutrino oscillation data along with predicted backgrounds. Note that the scale is not normalized to bin width so that event numbers may be more easily seen.

neutron efficiency almost cancels, with a resulting NC background neutron fraction of 56%, to be compared with our initial estimate of 50%.

The MiniBooNE neutrino mode oscillation sample is shown in Fig. 16. In the lowest 4 bins where the excess is significant, the neutron veto cut will reduce the ν_μ NC backgrounds by 30% for an overall background reduction of 21%.

The NUANCE simulation was also used to understand the ν_e CC signal events. In that sample 15% of events are actually CCπ events with pion absorption. This sample has associated neutrons in about 50% of events. This increases the estimated neutron fraction for ν_e signal events from the original estimate of 2% to 8% in the lowest energy bin.

This exercise points out that predicting the number of neutrons in both signal and background is complex and rests on many model assumptions. A calibration measurement of these neutron fractions in ν_μ CCQE and NCπ^0 will be a crucial step in verifying these predictions and demonstrating the viability of the method.

5.2 A 5σ oscillation sensitivity

The background rejection obtained with via a neutron capture veto does not, on its own, enable an increase in the MiniBooNE signal significance. However, it is possible with a reduction in background systematic error that is enabled by the neutron capture measurement. Table **??** summarizes the current MiniBooNE oscillation event numbers and errors in the lower energy region along with an estimate of those numbers in a new run with MiniBooNE+. The combination of background rejection with a reduction in systematic error on the background from 10.5% to 5% results in a 5σ excess if the underlying excess is indeed due to oscillations.

A reduction in the background systematic error at low energy where the NC backgrounds dominate can be obtained by measuring the neutron multiplicity distributions for NCπ^0 events where the π^0 are cleanly reconstructed as 2-ring events. Then this distribution can be used to better constrain the number of NCπ^0 and NCγ background events. A factor of 2 reduction in that systematic error should be possible with this extra neutron capture signature.

	no n-veto	with n-veto
background	479.3	380.7
statistical error	21.9	19.5
systematic error	50.5	19.0
relative systematic error	10.5%	5.0%
total error	54.0	27.3
data events	623.0	520.0
excess events	143.7	139.3
# σ	2.7	5.1

Table 2: MiniBooNE neutrino oscillation event counts and errors in the range $0.2 < E_\nu^{QE} < 0.55$. The numbers in the 2nd column are those from the existing MiniBooNE analysis. Note that this simple treatment of errors underestimates the significance of the excess due for the current data set. The 3rd column is the tally after application of an n-veto cut, a reduction in systematic error on the background to 5%, and the assumption that the underlying excess is due to oscillations.

5.3 Calibration of the neutron fraction in NC and CC events

In order to utilize known neutron multiplicity distributions in the oscillation analysis these distributions must be measured.

For CC events, one wants to know, as a function of reconstructed neutrino and, in particular at $E_\nu \approx 100 - 500$ MeV, the neutron fraction in the reaction $\nu_e C \to e^- X$ (Fig. 4a). This has been measured at this energy scale by LSND [32] in the $\nu_\mu C \to \mu^- X$ reaction as described earlier. The difference between ν_e and ν_μ can be calculated with consideration of the higher energy threshold in the ν_μ reaction. This will also be measured by MiniBooNE via $\nu_\mu C \to \mu^- X$ events that contain a neutron, identified with the n-capture signal. It is estimated (and used in the study above) that a 5% systematic error may be obtained.

For NC events, the desired quantity is the neutron fraction for the NC oscillation backgrounds, NCπ^0 and NCγ (Figs. 4b, 4c). The NCπ^0 background can be measured via $\nu_\mu C \to \pi^0 X$ where the π^0 is correctly identified in the detector. This measurement has previously been made by MiniBooNE [54, 38]. The extrapolation to the background NCπ^0 events is then performed with the detector simulation and is fairly model independent, depending mainly on π^0 kinematics.

The NCγ background may then be calculated from the radiative decay of the Δ with the production rate of the Δ constrained by the NCπ^0 measurement. The change of the Δ width in carbon is taken into account. This was the method used by MiniBooNE in the current analysis and has been vindicated with separate theoretical calculations [21, 15].

6 Δ s measurement

As introduced in Sec 3.2, a measurement of $R(p/n)$ is sensitive to the strange-quark contributions to the nucleon spin. A study of this was performed using the current MiniBooNE detector simulation together with realistic estimates of neutron capture efficiency.

The current MiniBooNE detector simulation with standard scintillation levels was employed. This approach allowed us to use currently existing "excursions" MC samples to estimate systematic errors. We are confident that the addition of scintillator will improve the situation, providing better reconstruction of nucleons and lowering the energy threshold.

To determine the MiniBooNE+ sensitivity to Δs, MC generated samples of neutrino NCE interactions corresponding to 2×10^{20} POT (approximately 1 year of running) were used. The effective efficiency for neutron capture and proton mis-id (Fig. 15) was applied to the $\nu p \to \nu p$ and $\nu n \to \nu n$ samples. Note that the underlying 50% n-capture efficiency grows with nucleon energy because of the probability to get multiple neutrons from a single primary neutron or proton.

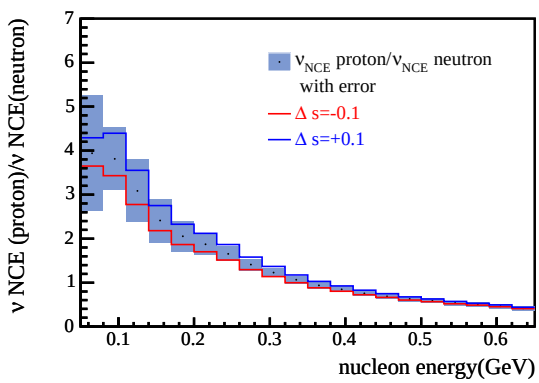


Figure 17: Simulated NC p/n ratio measurement for a $\Delta s = 0.0$. The red and blue lines show the expected change with $\Delta s = \pm 0.1$.

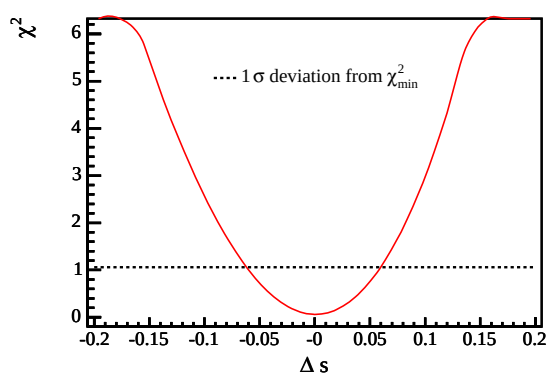


Figure 18: χ^2 of simulated data to a model with varying Δs values.

The measured proton-neutron ratio, $R(p/n)$, was calculated using simulated NC-neutron and NC-proton events with the neutron efficiency and proton mis-identification taken into account. The error bands on this quantity are determined by finding the r.m.s. spread of the result for each of the excursion simulations and the statistical error from a 2×10^{20} POT event sample. The results are shown as a function of nucleon energy in Fig. 17. The error on $R(p/n)$ integrated over nucleon energy is 12.5% and is dominated by uncertainties in detector effects. This is a conservative estimate on errors as dominant detector uncertainties are those due to the unknown nature of the inherent scintillation in MiniBooNE. The addition of a well-known scintillator will increase the light level and lower those uncertainties.

The simulated events in this exercise were produced by the NUANCE event generator which contains a model of NC elastic scattering and includes the dependence on the strange part of the axial form factor which is equal to Δs at $Q^2 = 0$. Thus the predicted change in $R(p/n)$ can be studied via variations in the MC as is shown with the red/blue curves in Fig. 17. A χ^2 comparison of the simulated $\Delta s = 0$ data to a family of Δs variations (Fig. 18) using the calculated errors results in an expected error on a Δs measurement of ± 0.06. This would be the best measurement of Δs from a neutrino experiment and would provide a important comparison to results from deep inelastic scattering.

Error	Value (%)
Statistical	5.3
Flux uncertainty	0.2
Cross section uncertainty (background processes)	2.4
Detector effects	11.0
Estimation of "dirt" events	1.2
Total	12.5

Table 3: The estimated total error on $R(p/n)$ as measured in MiniBooNE+ intergrated over nucleon energy along with the most important individual error contributions.

7 Implementation

In this section, we provide details of how to prepare and run MiniBooNE+ with the addition of scintillator.

7.1 Suggested plan for adding scintillator

We plan to add 300 kg of PPO to the 1×10^6 liters of MiniBooNE mineral oil (300 mg/L). A price quote for PPO from the supplier to NOvA is \$250/kg or \$75k for the entire 300 kg. The funds for this have been obtained from NSF-nuclear physics via the Indiana nuclear physics group. The solubility of PPO will allow us to add the entire 300 kg to the MiniBooNE 10 kl overflow and then introduce that into the main volume by recirculation. However, it would be prudent to do this addition in at least two steps by taking the concentration to about 50% of the desired amount and monitoring detector response with cosmic muons and muon-decay electrons. We may do recirculation without the addition of scintillator as a first step, as the MiniBooNE oil has not been recirculated since commissioning in 2002. After the initial mixing phase, estimated to take about 2 months, we anticipate stopping the recirculation.

7.2 Detector changes

Our base plan for running with scintillator is only to add scintillator with no other changes. New readout electronics could be considered, but are not required for the physics goals set here. The current rate of PMT and failures extrapolated for a 3-year run is not a problem. We estimate that the rate of electronics failures over that time period will be covered with our current supply of spares. There will likely be some changes to the computing infrastructure to keep up with hardware failures and security concerns, but an "as-needed" approach is our current plan.

7.3 Run plan

As shown in Sec. 5, vetoing on neutron capture and reducing the background errors will move the measurement toward statistics limited regime and 6.5×10^{20} POT will required required. When the MicroBooNE experiment is running, our assumption is that 2×10^{20} POT/year will be delivered to the Booster Neutrino Beamline (BNB). This sets a 3-year duration for the proposed scintillator phase of MiniBooNE. Preparation for running only requires the addition of scintillator (along with normal detector maintenance), which we estimate will require about 3 months with no beam requirement. We plan to add scintillator incrementally starting in mid-2014.

8 Conclusions and request

We have presented a plan for the MiniBooNE+ experiment which consists of the addition of 300 mg/L of scintillator to the existing MiniBooNE mineral oil and further running with 6.5×10^{20} POT. The scintillator will allow for the detection and and reconstruction of 2.2 MeV γ from neutron-capture which enables an additional discrimination of NC background events from CC oscillation events. The neutron-capture rate for both of these event types can be separately measured in MiniBooNE, thus eliminating dependence on neutron production model calculations. Therefore, a measurement of neutron-capture in oscillation events measures the NC backgrounds.

A measurement of the neutron-fraction in a new appearance oscillation search with MiniBooNE will increase the significance of the oscillation excess, if it maintains in the new data set, to near 5σ. With 6.5×10^{20} POT, the results of this search (before neutron capture cuts) should have similar sensitivity as existing search but with different systematic errors. The collection of 2×10^{20} POT will enable the Δs measurement along with a calibration and test of the neutron fraction in ν_μ CCCQ and CCπ^0 events.

This new phase of MiniBooNE would enable additional important studies such as the spin structure of nucleon (Δs) via NC elastic scattering, a low-energy measurement of the neutrino flux via the $\nu_\mu\ {}^{12}C \rightarrow \mu^-\ {}^{12}N_{\text{g.s.}}$ reaction, and a test of the quasielastic assumption in neutrino energy reconstruction. This effort will provide traning for Ph.D. students and postdocs and will yield important, highly-cited results over the next 5 years for a modest cost.

> *We are requesting approval for MiniBooNE+ which requires* 6.5×10^{20} *protons on target. The* Δs *measurement and calibration of the oscillation event neutron fraction can be obtained with* 2×10^{20} *protons on target which would provide an early test of the viability of the new oscillation measurement along with a physics result. We request to begin this new phase of running in mid-2014, concurrently with the MicroBooNE experiment.*

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