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Measuring ν_μ Charged-Current Interactions in MiniBooNE

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MiniBooNE seeks to confirm or refute the LSND $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation signal with high statistical significance and different systematics. MiniBooNE has accumulated the world's largest ~1 GeV neutrino data set. MiniBooNE employs a cosmic muon calibration system to study the reconstruction of the energies and directions of muons in the detector. Progress of measurements of the ν_μ charged-current quasi-elastic and single pion production cross sections are presented.

1. The Importance of Measuring Muons in MiniBooNE

MiniBooNE [1] is a neutrino oscillation experiment at Fermilab designed to confirm or rule out the hypothesis that the LSND $\overline{\nu}_e$ excess [2] is due to $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations. A general description of the experiment can be found elsewhere in these proceedings [3].

The neutrino energy reconstruction is critical to the success of the MiniBooNE oscillation and cross section analyses. Charged current quasi-elastic (CCQE) events ($\nu_\mu n \to \mu^- p$) are typically used to measure the neutrino energy spectrum because they have simple kinematics. Neglecting the nucleon target momentum, the reconstructed quasi-elastic neutrino energy can be expressed in terms of the momentum of the muon. Therefore, the muon energy and direction measurements completely determine the neutrino energy measurement.

The MiniBooNE cosmic muon calibration system [4] uses stopping muons and their decay electrons to calibrate the event reconstruction algorithms. This system provides a precise calibration of the energy, direction and position of muons for the complete range of muon energies of interest in the experiment, 100-900 MeV.

2. Cosmic Muon Calibration System

The muon calibration system consists of a muon tracker located above the detector, and seven scintillator cubes deployed inside the detector. The entering position and direction of a cosmic muon impinging on the detector are determined by the muon tracker, and the stopping position is determined by the location of the cube in the case where the muon stops and decays inside the one of the cubes. The muon

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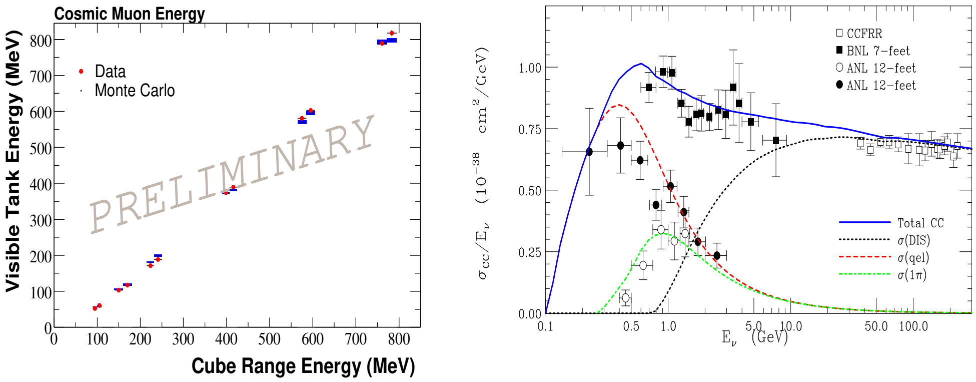

Fig. 1. The energy of cosmic muons in MiniBooNE, and the ν_μ interaction cross sections shown as a function of neutrino energy.

energy is then obtained from the range with an uncertainty due to range straggling of approximately 3% [5]. The muon range kinetic energy measurement is compared to the visible energy as reconstructed by the event fitters on an event by event basis. This gives the absolute energy scale calibration of the MiniBooNE detector.

The event fitter returns an "electron equivalent energy," which is the energy of an electron that would have produced the same number of photoelectrons in the detector [6]. The visible energy of cosmic muons is plotted against the kinetic energy calculated from the range using the cubes in Fig. 1a. There is good agreement between data and Monte Carlo. Using the information in Fig. 1a, the visible energy measurement is converted to a muon kinetic energy, which is used to calculate the neutrino quasi-elastic energy. From the cosmic muon calibration system, the muon kinetic energy uncertainty is measured to be 5%, and the angular resolution to be 45 mrad, leading to a neutrino energy uncertainty of ~10%.

3. Measuring ν_μ Events in MiniBooNE

The MiniBooNE event rate prediction is described elsewhere [7]. The ν_μ charged-current interaction cross section as a function of neutrino energy is shown in Fig. 1b [8]. In MiniBooNE's energy range, the dominant cross section are CCQE, which comprises 40% of the expected neutrino events, and charged current resonant single pion (CC1π) events, which are expected to comprise 25% of the total event rate.

3.1. *Charged-Current Quasi-Elastic Events*

CCQE events are interesting because they are the dominant event channel used in successful neutrino oscillation searches. MiniBooNE's CCQE event selection requires that candidate events pass cosmic background and fiducial volume cuts, and that the event topology be consistent with expectations for a single muon passing through

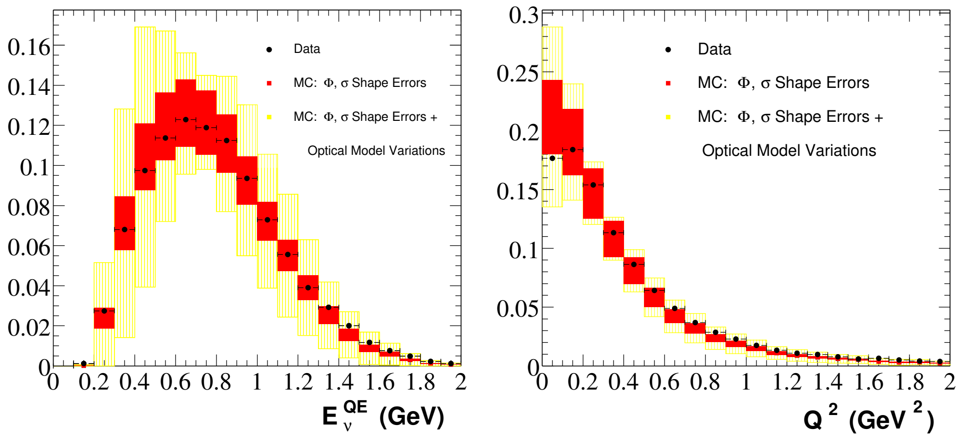

Fig. 2. Distribution of reconstructed quasi-elastic energy of MiniBooNE ν_μ event candidates. Distribution of reconstructed momentum transfer of MiniBooNE ν_μ event candidates. The figures both show data in black points, with statistical errors, and Monte Carlo expectations in colored bands with systematic uncertainties.

the detector [7]. Monte Carlo studies indicate the cuts are 55% efficient within the 500cm fiducial volume, producing an 80% pure CCQE event sample.

The reconstructed neutrino quasi-elastic energy is shown in Fig. 2a, and the Q^2 distribution in Fig. 2b, for 1.6×10^{20} POT. Ongoing studies of the transmission of light in mineral oil are expected to improve the optical variations dramatically.

Note that the shape of the neutrino energy spectrum is somewhat harder in the data than the Monte Carlo predicts, although the deviations sit within the limits of the current error bands. Note also the hint of a low Q^2 deficit which may indicate a nuclear model deficiency. This is an active area of study within the neutrino community.

3.2. *Charged-Current Single Pion Events*

Charged-current single pion ($\nu_\mu p \to \mu^-\pi^+ p$) production has been studied since the advent of high energy accelerator neutrino beams but the cross section for such processes in the MiniBooNE energy range have not been sufficiently explored. We describe here the first look at a sample of CC1π events in MiniBooNE.

MiniBooNE's CC1π event selection requires the simple yet robust cut of two Michel electrons following the neutrino interaction. The majority of pions emitted from these events stop in the detector oil. These decay quickly to muons, which then decay to Michel electrons. The muons emitted from the neutrino interaction also come to rest, and the majority of these decay to Michel electrons. Applying this requirement to 2.7×10^{20} POT of MiniBooNE data yields over 36,000 CC1π candidate events. The Monte Carlo predictions indicate a purity of 80% for this sample. This data set is larger by a factor of 4 than all CC1π neutrino data published to date.

The Michel electrons from the CC1π candidate events are used to verify the composition of the data set. The distance from each Michel to the end of the muon track in calculated. Assuming that the closer Michel is associated with the μ^- from the neutrino interaction, and the farther Michel is associated with the π^+ decay, we expect the closer Michels to have a shorter lifetime. This occurs because the μ^- are captured by carbon nuclei at a rate of 8%, changing the expected lifetime from 2197.03±0.04 ns [9] to 2026.3±1.5 ns [10]. The observed muon lifetimes for the close and far Michel samples are 2070±16 ns and 2242±17 ns, respectively. Again, note that the observed lifetimes do not yet include systematic uncertainties.

While we are able to successfully extract CC1π events with high purity, full event reconstruction studies are still in progress as the complex final state requires additional reconstruction handles that are not yet fully developed.

4. Conclusions

MiniBooNE has already amassed the world's largest neutrino data set in the ~1 GeV region in its quest to confirm or rule out the LSND oscillation signal. Using a cosmic muon calibration system, we measure the energy of muons to 5%, and the directions to better than 45 mrad. This leads to an uncertainty in the reconstruction of quasi-elastic neutrino energy of ~10%. We are currently examining large CCQE and CC1π data sets, and expect to have cross section measurements and ν_μ disappearance oscillation results from these data samples in 2005.

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