Introduction to MiniBooNE and ν_μ charged-current quasi-elastic results

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Abstract. The MiniBooNE experiment is described together with the procedures used to obtain a result for $\nu_\mu \to \nu_e$ oscillations. (The oscillation results are described in the companion talk of M. Sorel.) Results are given here for the charged-current quasi-elastic (CCQE) cross section, $\nu_\mu n \to \mu^- p$. It is found that the simple relativistic Fermi gas nuclear model with Fermi momentum, $P_F = 220$ MeV/c and binding energy $E_B = 34$ MeV is insufficient to describe the reaction for any values of the axial vector mass M_A. It was found necessary to add a new empirical Pauli blocking parameter, κ. With this new term, the best values found were $M_A = 1.23 \pm 0.20$ GeV and $\kappa = 1.019 \pm 0.011$.

1. Introduction

The MiniBooNE experiment runs at Fermilab with the principal goal of addressing the LSND anomaly found for $\nu_\mu \to \nu_e$ oscillations[1]. In that experiment a 3.8σ excess of $\bar{\nu_e}$ events was found in a $\bar{\nu_\mu}$ beam. This result was incompatible with the measured oscillation results from solar and atmospheric neutrinos if there were only the three standard neutrinos.

2. The MiniBooNE experiment

The MiniBooNE experiment was designed to have the same ratio of target-detector distance L to neutrino energy E as the LSND experiment, but with each of these individual parameters much larger for MiniBooNE than for LSND. The MiniBooNE experiment uses 8 GeV KE protons from the Fermilab booster. These strike a 71 cm Be target. Outgoing positive pions and kaons are focussed by a pulsed magnetic horn. These secondary particles then travel down a 50 m decay region of radius 91 cm and then strike an iron absorber. The detector is at a distance of 541 m from the front of the target; the region between the iron absorber and the detector is filled with dirt. There are about 4×10^{12} protons per 1.6 μs beam spill at an average pulse rate of about 4 Hz. 5.58×10^{20} protons on target were collected in the initial run. The neutrino spectrum at the detector peaks at about 0.7 GeV. The major categories of events are 39% CCQE, 25% charged-current (CC) $\pi^\pm$, 16% neutral current (NC) elastic scattering, and 8% NC π^0. The fraction of intrinsic ν_e is 0.6%, from μ and K decays. $\bar{\nu}$'s are about 1.4% of the events.

The MiniBooNE detector is a 12.2 m diameter sphere (10 m "fiducial" diameter), filled with 800 t of mineral oil. The oil (CH_2) has $\rho = 0.86$ g/cm^3 and $n = 1.47$. There are 1280 eight-inch photomultipliers (pmts) facing inwards. Behind a light-tight shield 35 cm from the outer wall, there are 240 eight-inch cosmic ray veto pmts facing outwards. The detector center is 1.9 m above the center of the neutrino beam, and there is 3 m dirt overburden above the detector.

The detector has a 19.2 μs time window starting 4μs before the beam. 75% of the photomultipliers have a 1.7 ns time resolution and the rest have 1.2 ns resolution. Making the simple cuts that there be less than 6 veto hits and more than 200 tank hits (to remove electrons from μ decay) removes almost all of the beam-unrelated background.

In order to detect decaying pions and muons from neutrino interactions, events are divided into 100 ns bins for subevent clusters. Most of the light generated by the charged tracks is Cherenkov light. The Cherenkov/scintillation ratio is about 8/1. Flourescence and attenuation are important and are functions of frequency. Cherenkov light is prompt and at a fixed angle to the track; scintillation light and fluorescence light are delayed and approximately isotropic. The ratio of prompt/delayed light at the photomultipliers is about 3/1 on the average.

3. Event types, event reconstructions

Muons are produced in most CC events. There are usually 2 subevents (only 8% of the muons are captured) if the muons do not exit the detector. A muon Cherenkov ring is sharp on the outside. It is fuzzy on the inside if the muon stops, or is filled in if the muon exits. ν_e events generally have one subevent and the cherenkov ring is fuzzy from the electromagnetic shower. π^0 have two Cherenkov rings, one for each decay photon. If one photon is weak or exits without converting, then NC π^0 events mimic ν_e events.

Three reconstruction hypotheses are tried:

(i) One outgoing muon track,
(ii) One outgoing electron track,
(iii) Two tracks (aimed at π^0 events).

MiniBooNE has maintained two reconstruction streams. The second is an elaboration of the first (sfitter), but takes an o.m. more computer time. It obtains a 22 cm position error and a 2.8^o one-track angle error; for π^0 it has about a 20 MeV π^0 mass resolution.

4. Simulations

Simulations used measured pion production cross sections from Harp[2], BNL910[3], and some earlier experiments[4]. GEANT4 was used for following produced particles through the magnetic horn, decay region, and into the detector. V3 Nuance[5] was used for neutrino cross sections (with some modifications from MiniBooNE measurements and other improvements). A detailed optical model for the detector was prepared using GEANT3. There were 40 optical model parameters, obtained both from external measurements and in situ measurements.

5. Oscillation analysis

Signal events were defined as ν_e CCQE events. The elaborate reconstruction used simple cuts based on the track reconstruction (TB=track-based) to separate the event. The cuts use:

(i) Likelihood of one track electron fit vs one track muon fit,
(ii) Likelihood of one track electron fit vs two track fit,
(iii) Mass of π^0 in the two track fit.

The sfitter used a method new to physics, boosted decision trees[6] (BDT) with many variables (172). To build a decision tree one finds the best variable and value to divide the sample to make one subsample mostly signal and the other subsample mostly background. This process is then repeated on each of the subsamples until each is mostly signal or backround or has too few events. The final subsamples are called leaves. The decision tree is trained using Monte Carlo events. The decision tree method is more than a quarter of a century old and has serious problems. These problems are overcome by boosting. Here, one looks at the events which end up misclassified and increases their weight. A new decision tree is made with these problematic events having a higher weight. This process is then repeated many times. If each tree gives a score of 1 for a signal leaf and −1 for a background leaf, then the final score for a given event is just the sum (possibly weighted) of the scores of all the individual trees. This is found to be a very powerful method of event classification.

There are two categories of backgrounds, those due to intrinsic ν_e events and those due to mis-identified ν_μ events. The percentage of all background due to various intrinsic ν_e events for the TB analysis is 31% from μ-decay, 24% from $K^\pm$ decay and 6% from K^0 decay. The percentage of all background due to various mis-identifications is 20% NC π^0 events, 7% $\Delta(1232)$-radiative decay events, 1% $\pi^\pm$ events and 11% miscellaneous.

The model systematic uncertainties in ν_e background differ for the TB and the BDT analyses. The largest errors for the TB (BDT) analyses are 6.2% (4.3%) for flux from π^+/μ^+ decay, 12.3% (10.5%) for neutrino cross sections, 6.1% (10.5%) for the optical model and 7.5% (10.8%) for the data-acquisition electronics model. These model errors are then further constrained with MB data.

The results of the oscillation analysis are given in the companion talk of M. Sorel.

6. Charged-current ν_μ quasi-elastic events

The MiniBooNE experiment has collected close to two orders of magnitude more CCQE events than any previous experiment. CCQE interactions account for 39% of all neutrino interactions at MiniBooNE, before cuts. The 193,709 events selected had two subevents with the second subevent being consistent in position with μ-decay and having < 200 tank hits. The efficiency of this cut was 35%. The sample is 74% pure; the backgrounds are mostly CC single pion production. The kinetic energy resolution is 7% at 0.3 GeV and the angular resolution is about 5^o. The Q^2 values were mostly in the 0-1 $(\mathrm{GeV})^2$ region.

Modern CCQE spectra on nuclear targets have been fit using a relativistic Fermi gas nuclear model with $P_F = 220$ MeV/c, $E_B = 34$ Mev (Carbon) and vector form factors F_V taken from electron experiments. The axial vector form factor F_A is given as:

$$F_A = g_A/(1 + Q^2/M_A^2)^2,$$

with $g_A = 1.2671$. Previous low statistics experiments found $M_A \approx 1.03$ GeV. In Figures 1 and 2 the Q^2 and E_ν dependencies of the data is shown. The dashed lines show the results using the parameterization of the previous experiments.

In the Smith and Moniz model[7], carbon is described by a collection of incoherent Fermi gas particles. All complications come from the hadronic tensor, $(W_{\mu\nu})_{lab}$.

$$(W_{\mu\nu})_{lab} = \int_{Elo}^{Ehi} f(\vec{k}, \vec{q}, \omega) T_{\mu\nu},$$

where:

(i) $f(\vec{k}, \vec{q}, \omega)dE$ is the density function from energy conservation and distribution of states,

(ii) $T_{\mu\nu} = T_{\mu\nu}(F_1, F_2, F_A, F_P)$ is the nucleon tensor and the F's are the various form factors,

(iii) ω is the energy transfer,

(iv) Ehi is the highest energy state of the nucleon $= \sqrt{P_F^2 + M^2}$,

(v) Elo is the lowest energy state of the nucleon $= \sqrt{P_F^2 + M^2} - \omega_{eff}$ for the QE interaction.

To get agreement with data, an empirical correction was made to this model. Elo was changed to $Elo_{new} = \kappa Elo_{old}$. This effectively changes the initial energy level distributions. The best fit to Q^2 was found to be $M_A = 1.23 \pm 0.20 GeV$; $\kappa = 1.019 \pm 0.011$[8]. The Q^2 fit χ^2/dof went from 48.8/31 without the κ term to 32.8/30 with that term added. The results are shown in Figures 1 and 2. This data should provide a guide leading to a better nuclear model. The resultant CCQE cross section model, as constrained by the high statistics CCQE events, was important for predicting ν_e CCQE signal events for the MiniBooNE oscillation analysis.

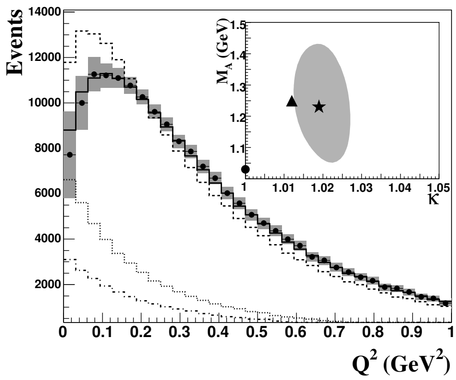

Figure 1. Reconstructed Q^2 for ν_μ CCQE events including systematic errors. The simulation, before (dashed) and after (solid) the fit, is normalized to the data. The dotted (dot-dash) curve shows backgrounds that are not CCQE (not "CCQE-like"). The inset shows the 1σ CL contour for the best-fit parameters (star), along with the starting values (circle), and fit results after varying background shape (triangle).

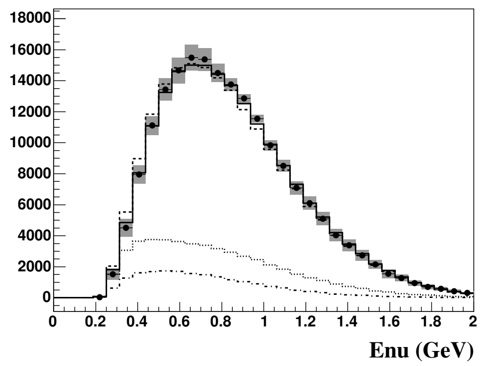

Figure 2. Reconstructed E_ν for ν_μ CCQE events including systematic errors. The simulation, before (dashed) and after (solid) the fit, is normalized to the data. The dotted (dot-dash) curve shows backgrounds that are not CCQE (not "CCQE-like").

[1] Athanassopoulos C. *et al* 1995 *Phys. Rev. Lett.* **75** 2650
Athanassopoulos C. *et al* 1996 *Phys. Rev. Lett.* **77** 3082
Athanassopoulos C. *et al* 1998 *Phys. Rev. Lett.* **81** 1774
Aguilar A. *et al* 2001 *Phys. Rev.* D **64** 112007
[2] Catanesi MG *et al* 2007 *Preprint* hep-ex/0702024
[3] Chemakin I. *et al* 2007 *Preprint* arXiv:0707.3275v1 [nucl-ex] submitted to *Phys. Rev.* C
[4] Abbott T. *et al* 1992 *Phys. Rev.* D **45** 3906
Allaby JV *et al* 1970 *Preprint* CERN 70-12
Dekkers D. *et al* 1965 *Phys. Rev.* B **137** 962
Marmer GJ *et al* 1969 *Phys. Rev.* **179** 1294
Eichten T. *et al* 1972 *Nucl. Phys.* B **44** 333
Aleshin *et al* 1977 *Preprint* ITEP-77-80
Vorontsov *et al* 1988 *Preprint* ITEP-88-11
[5] Casper D 2002 *Nucl. Phys. Proc. Suppl.* **112** 161
[6] Roe BP, Yang HJ, Zhu J. Liu Y, Stancu I, and McGregor G 2005 *Nucl. Instrum. & Meth.* A **543** 577-84
Yang HJ, Roe BP, and Zhu J 2005 *Nucl. Instrum. & Meth.* A **555** 370-85
Yang HJ, Roe BP, and Zhu J 2007 *Nucl. Instrum. & Meth.* A **574** 342-9
[7] Smith RA and Moniz EJ 1972 *Nucl. Phys.* B **43** 605 *erratum: ibid* 1975 B**101** 547
Moniz, EJ *et al* 1971 *Phys. Rev. Lett.* **26** 445
[8] Aquilar-Arevalo A. *et al* 2007 *Preprint* arXiv:0706.0926 [hep-ex] Submitted to *Phys. Rev. Lett.*