Challenges In Extracting Charged Current Quasi-Elastic Model Information in MiniBooNE's Anti-Neutrino Data

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Abstract. Using a high-statistics sample of anti-neutrino charged current quasi-elastic (CCQE) events, MiniBooNE reports the challenges in measuring parameters within the Relativistic Fermi Gas model. As the CCQE analysis has been completed in MiniBooNE's neutrino data, particular attention is paid to the differences in CCQE interactions between the two running modes.

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CCQE MODEL TUNING AT MINIBOONE

At MiniBooNE's sub-GeV energies, interaction rates are dominated by the CCQE cross section. In neutrino mode, describing these interactions well was an essential constraint in the oscillation search to either refute or confirm the controversial LSND results[1]. Two parameters in the Relativistic Fermi Gas (RFG) model were simultaneously tuned to improve data - Monte Carlo agreement[2]. The first is the axial mass form factor M_A ($\sigma = \sigma(F_A)$):

$$F_A(Q^2) = g_A \Big/ \left(1 + \frac{Q^2}{M_A{}^2}\right)^2 \tag{1}$$

where Q^2 is the four momentum transfer and $g_A = 1.267$ is well known from beta decay experiments. MiniBooNE assumes a dipole form for $F_A(Q^2)$. Tuning M_A alone left a data deficit in the low Q^2 region, so a pauli-blocking parameter κ was introduced and fit together with M_A. The scale factor κ controls the lower bound on the available nucleon energy:

$$E_{lo} = \kappa\left(\sqrt{p_F^2 + M^2} - \omega + E_B\right) \tag{2}$$

where E_B is the binding energy of the nucleon, M is the mass of the nucleon, p_F the Fermi momentum, and ω the energy transfer.

MiniBooNE measured $M_A = 1.35 \pm 0.17$ GeV and $\kappa = 1.007^{+0.007}_{-\infty}$ for sub-GeV neutrino CCQE events on a CH_2 target[3].

INTERACTIONS FROM MINIBOONE'S ANTI-NEUTRINO BEAM

The neutrino mode CCQE analysis benefitted from both a low wrong-sign anti-neutrino background and a single nuclear scattering target. Unfortunately the same is not true in the anti-neutrino beam. The wrong sign neutrino contamination is more significant and the anti-neutrinos scatter off bound nucleons in carbon and free nucleons in hydrogen. The interaction is described in Figure 1, while Table 1 summarizes the prediction for MiniBooNE contamination and free nucleon scattering based on MC simulations. We use the NUANCE neutrino interaction generator[4], which uses the RFG model[5] for CCQE scattering[6].

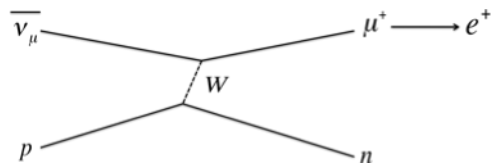

FIGURE 1. An anti-neutrino CCQE interaction. MiniBooNE reconstructs the event based on kinematic measurements of the outgoing muon.

TABLE 1. Summary of wrong sign contamination and free nucleon scattering in MiniBooNE's two running modes, based on Monte Carlo simulation.

Component	Neutrino Beam	Anti-Neutrino Beam
Right Sign CCQE	77 %	54 %
Wrong Sign CCQE	2 %	22 %
QE H2 Scattering	0 %	19 %

The wrong sign contamination will be measured from the data and subtracted from the CCQE signal, but the QE model parameter measurement is not so straightforward. While the parameter κ measured from the neutrino beam interactions is consistent with 1 and consequently perhaps not strictly needed, it is less clear what is the correct approach to take with regard to the axial mass M_A. In the past M_A was thought to be well known at an appreciably lower value than what MiniBooNE measured. Based on bubble chamber data, M_A was measured to be 1.03 ± 0.02 GeV[7]. Other neutrino experiments besides MiniBooNE have also measured higher values of M_A (see Table 2).

TABLE 2. Some M_A measurements from recent neutrino experiments, most significantly higher than the previous bubble chamber measurement of 1.03 ± 0.02 GeV[7].

Source	Measured M_A (GeV)
K2K SciFi[8]	1.20 ± 0.12
K2K SciBar[9]	1.14 ± 0.11
MINOS[10]	1.26 ± 0.17
NOMAD[11]	1.07 ± 0.07
MiniBooNE[3]	1.35 ± 0.17

Within the RFG model, it is possible that M_A is a nuclear dependent parameter and may also be a function of the incident neutrino energy. We should accommodate this possibility and not strictly assume a single M_A for all of our anti-neutrino interactions. Of course it is also possible nuclear effects such as charge exchange/absorption and final state interactions are obfuscating the various measurements of M_A. Regardless, when fixing M_A and κ at their previous "world values" of 1.02 GeV and 1.000 respectively, MiniBooNE sees poor data - Monte Carlo agreement in the kinematic variables. See Figures 2 and 3.

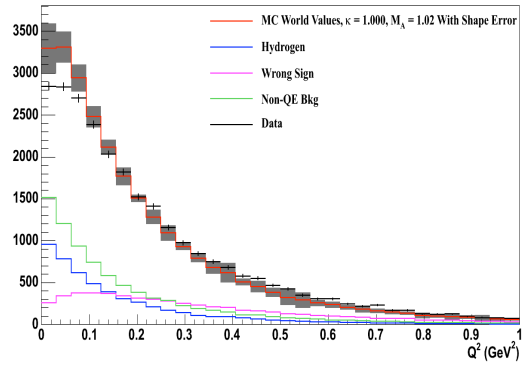

FIGURE 2. Reconstructed four-momentum transfer Q^2 with QE model parameters evaluated at the world values $M_A = 1.02$ GeV, $\kappa = 1.000$ compared to data. Significant shape discrepancy at both low and high Q^2 is observed. The complicating backgrounds are plotted. Distributions have arbitrary units.

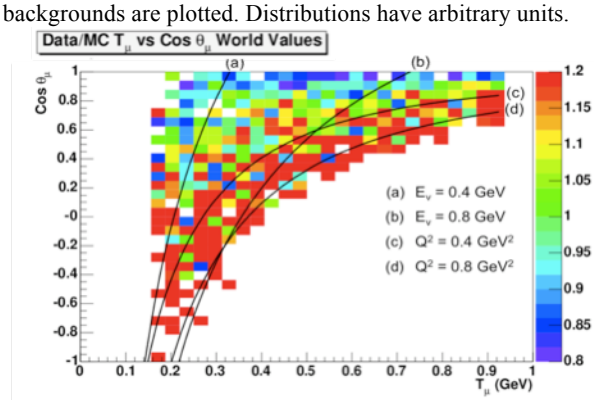

FIGURE 3. Ratio of data / Monte Carlo in kinetic energy T_μ vs. cosine of the scattering angle $\cos\theta_\mu$ of the outgoing muon for $M_A = 1.02$ GeV, $\kappa = 1.000$. Discrepancies follow lines of constant Q^2 and not E_ν. This suggests the disagreement may originate in the cross section and not the flux prediction.

However, if we apply $M_A = 1.35$ GeV and $\kappa = 1.007$, the values measured in MiniBooNE's neutrino mode, we see improved data - Monte Carlo agreement. See Figures 4 and 5. The axial mass $M_A = 1.35$ GeV is applied to all QE events, regardless of sign and scattering target.

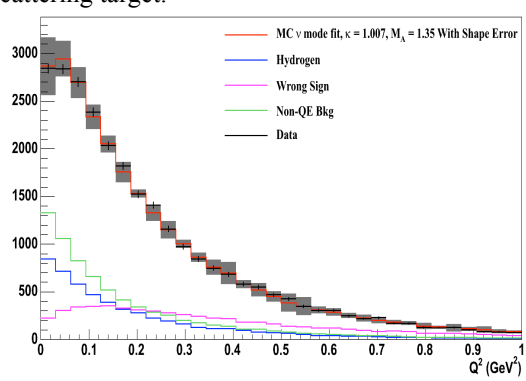

FIGURE 4. Reconstructed four-momentum transfer Q^2 with QE model parameters evaluated at the neutrino mode best fit values compared to data. The shape disagreement observed when using the world values of M_A and κ is improved. The complicating backgrounds are plotted. Distributions have arbitrary units.

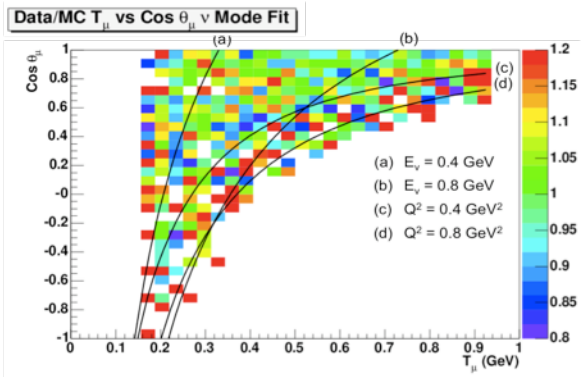

FIGURE 5. Ratio of data / Monte Carlo in kinetic energy T_μ vs. cosine of the scattering angle Cos θ_μ of the outgoing muon for M_A = 1.02 GeV, κ = 1.000. The systematic disagreement observed when using M_A and κ world values is improved by applying those measured in MiniBooNE's neutrino mode.

We do not mean to suggest the resolution to the task of measuring CCQE values in anti-neutrino mode is to blindly apply those found in neutrino mode. Rather, the improved data - Monte Carlo agreement when using the neutrino mode values suggests that pursuing to "fix" the discrepancy through the measurement of M_A and κ is promising.

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REFERENCES

1. C. Athanassopoulos *et al*., Phys. Rev. Lett. **75**, 2650 (1995); **77**, 3082 (1996); **81**, 1774 (1998).
2. A. A. Aguilar-Arevalo *et al.*, Phys. Rev. Lett. **100,** 032301 (2008).
3. T. Katori, reference in these proceedings.
4. D. Casper, Nucl. Phys. B, Proc. Suppl. **112**, 161 (2002).
5. S. Agostinelli *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).
6. R. A. Smith and E. J. Moniz, Nucl. Phys. **B43**, 605 (1972); **B101**, 547 (1975).
7. R. Gran *et al.* (K2K Collaboration), Phys. Rev. D **74**, 052002 (2006).
8. R. Gran *et al.*, Phys. Rev. **D74**, 052002 (2006).
9. AIP Conf. Proc. **967**, 117 (2007).
10. Dorman, M, reference in these proceedings.
11. V. Lyunushkin, *et al.* 0812.4543v3 [hep-ex].