Results for CCQE scattering with the MINOS near detector

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Abstract. The MINOS experiment has the world’s largest data set of neutrino interactions in the 1-10 GeV range. In addition, this data set is for neutrino interactions on iron, allowing us to explore the nuclear effects on neutrino scattering. We present preliminary results from a low hadronic energy, quasielastic enhanced sample of neutrino-iron interactions observed by the MINOS Near Detector in the NuMI neutrino beam at Fermilab. From a shape fit to the $Q^2$ distribution for these events, we extract a value for the effective axial-vector mass $M_A$ which best describes that distribution. We discuss the very low $Q^2$ behavior of this sample and the most important systematic effects for this measurement. Then we explore how we can increase our sensitivity to $M_A$ by adding exclusive final state selections to the $Q^2$ shape fit.

1. Introduction
The Main Injector Neutrino Oscillation Search (MINOS) experiment measures the spectrum of neutrinos produced by the Neutrinos at the Main Injector (NuMI) facility at Fermilab [1]. This is done using the two tracking-sampling calorimeters detectors. The 0.98 kt Near Detector (ND) is located on the Fermilab site, and the Far Detector (FD) is located 734 km away in Soudan, MN and has a mass of 5.4 kt [2]. MINOS was designed to measure the neutrino mass squared difference $\Delta m^2_{32}$ and the neutrino mixing angle $\theta_{23}$ by looking for the absence of muon neutrinos at the FD relative to the ND. MINOS has made the single most accurate measurement of the atmospheric mass difference ($\Delta m^2_{32}$) [3].

The ND is located 1 km from the NuMI target and records several neutrino interactions in each beam spill. This gives MINOS a high statistics sample of neutrino events for making neutrino-nucleus interaction measurements. This document presents a preliminary measurement of the charged current quasi-elastic (CCQE) scattering model parameter $M_A^{QE}$ [4] which parameterizes the dipole axial-vector form factor. Early neutrino experiments have been insufficient to fully constrain the CCQE cross-section, and the CCQE cross-section may constitute a large systematic uncertainty for future neutrino oscillation experiments such as NO$\nu$A and T2K.
2. Charged Current Quasi-Elastic Scattering

The neutrino-nucleon CCQE differential cross-section with respect to the squared four momentum transfer between the lepton and the hadron $q^2 = -Q^2$ is [5]:

$$\frac{d\sigma(\nu \mu n \rightarrow \mu^- p)}{dq^2} = \frac{M^2 G_F^2 \cos^2(\theta_W)}{8\pi E_\nu^2} \left[ A(q^2) - B(q^2) \frac{s-u}{M^2} + C(q^2) \frac{(s-u)^2}{M^4} \right]$$

(1)

where $(s-u) = 4E_\nu M + q^2 - m^2_l$; $m_l$ is the mass of the outgoing charged lepton, $M$ is the mass of the target nucleon, and; $A(q^2)$, $B(q^2)$ and $C(q^2)$ are functions of the nucleon vector form factor and the nucleon axial-vector form factor (where the pseudo-scalar form factor has been neglected). The vector form factors are well measured by electron scattering experiments, which leaves the uncertainty due to the axial-vector form factor as the dominant uncertainty in the CCQE differential cross-section. The axial-vector form factor can be parameterized as a dipole:

$$F_A(q^2) = \frac{F_A(0)}{\left( 1 + \frac{q^2}{M_A^2} \right)^2}$$

(2)

where $M_A$ is the axial-vector mass and $F_A(0)$ is well known from the $\beta$ decay of neutrons. In this parameterization of the axial-vector form factor the uncertainty in the CCQE cross-section is tied to the uncertainty in $M_A$. However in CCQE neutrino-nucleus scattering there are additional nuclear effects to consider.

We measure the value of $M_A$ by observing the $Q^2$ spectrum of CCQE scattering interactions. Changes in $M_A$ will result in changes in the overall interaction rate and shape of the $Q^2$ spectrum. As of 2002, the world average for $M_A$ was $1.026 \pm 0.021$ GeV [6]. This average is dominated by experiments performed using deuterium targets such as the measurements made at Argonne National Lab (ANL) and Brookhaven National Lab (BNL) [7][8]. The modern experiments K2K and MiniBooNE have both measured larger values of $M_A$ with K2K measuring $M_A$ to be $1.20 \pm 0.12$ [9] and MiniBooNE measured both $1.23 \pm 0.20$ [10] and $1.35 \pm 0.17$ [11] both using carbon targets.

3. Event Selection

We select charged current-like (CC-like) flux-tuned[1] MC[12] and data events using the procedure in [3]. Three criteria are then used to enhance the CCQE content of the sample. First, we require that there be exactly one reconstructed track in the event. This removes mostly deep inelastic scattering (DIS) events where a second track may be reconstructed from the highly energetic vertex hadron shower. Next, we require that the track stops within the MINOS ND, to ensure that the muon energy is reconstructed using range via $dE/dx$, which has greater resolution than curvature in the magnetic field of the detector. Third we require that the reconstructed shower energy is less than 250 MeV, removing both DIS and resonance production interactions which usually have larger more energetic vertex hadronic showers. These selection criteria produce a sample that is 61% pure CCQE events and is 53% efficient at selecting CCQE events that are in the CC-like sample.

We use a second event selection procedure to examine the low $Q^2$ behavior of the background to the CCQE analysis. As for the CCQE selection we select CC-like events as detailed in [3], then we select based on the reconstructed invariant mass $W$. We define events with reconstructed $W < 1.3$ (GeV/$c^2$) to be in the $QE/\Delta$ regime, and we define events with reconstructed $1.3 < W < 2.0$ (GeV/$c^2$) to be in the DIS to resonance transition regime. These values are chosen to let us explore different regions of our interaction model (NEUGEN).
4. Comparisons of Data to MC
Figure 1 shows the data and MC comparisons of the reconstructed $Q^2_{QE}$ for the CCQE-like selected sample and the reconstructed $Q^2$ for the transition sample. The CCQE-like sample contains a total of 345,000 events in data and only 293,000 events in the tuned MC. The transition sample contains 760,000 events in data and 690,000 events in the tuned MC.

There are two ways to reconstruct the $Q^2$ for a given event. For greater resolution when examining a QE-like sample it is possible to use the relatively simple kinematics of the QE interaction to reconstruct a high precision value for $Q^2$:

$$E_{\nu}^{QE} = \frac{(m_N + \epsilon_\mu)E_\mu - 2(2m_N\epsilon_B + \epsilon_B^2 + m_\mu^2)/2}{m_N + \epsilon_B - E_\mu + p_\mu\cos(\theta_\mu)}$$

$$Q^2 = -2E_\nu [E_\mu - p_\mu \cos(\theta_\mu)] + m_\mu^2$$  (3)

Where $\epsilon_B = 34$ MeV is the nuclear binding energy. Although any non-QE events in the sample will be systematically mis-reconstructed using this formula the mis-reconstruction should be the same for both data and MC. However if the sample is not sufficiently pure CCQE then it becomes necessary to calculate $Q^2$ differently. That is done by calculating neutrino energy as $E_\nu = E_\mu + E_{\text{shower}}$, then using this value for the neutrino energy in eq. 3. Figure 1 shows that the flux tuned MC mis-models the total rate of and the shape of both the CCQE-like sample and the transition sample, both requiring additional suppression of the low $Q^2$ region along with an overall flattening of the spectrum to better describe the data.

5. Fit Procedure
The total exposure of our MC is approximately four times the exposure of our data. We fit the flux tuned MC to our data by minimizing the expression

$$\chi^2_{MCstats} = \sum_{i=1}^{N_{bins}} \frac{(o_i - e_i(\alpha_1, \ldots, \alpha_N))^2}{o_i + S_i(\alpha_1, \ldots, \alpha_N)} + \sum_{j=2}^{N} \frac{\Delta \alpha_j^2}{\sigma_{\alpha_j}^2}$$  (4)

using an iterative procedure. In equation 4, $o_i$ is the number of observed events in data for bin $i$, $e_i(\alpha_1, \ldots, \alpha_N)$ is the number of events in bin $i$ as predicted by our MC for the given fit parameters,
$\alpha_j$ is the $j^{th}$ fit parameter, $S$ is the ratio of the data total POT to the MC total POT. The penalty term is calculated from $\Delta \alpha_j$, the difference between the $j^{th}$ systematic parameter and that parameter’s nominal value, and $\sigma_{\alpha_j}$ the 1σ uncertainty on the $j^{th}$ systematic parameter.

We fit the data using four parameters; one free parameter, $M_A^{QE}$, and three nuisance parameters: the muon energy scale which has a 1σ uncertainty of 2% [1]). The resonance production axial-vector mass $M_A^{Res}$ which has a nominal value of 1.12 GeV and has a 1σ uncertainty of 15% [1]. The final systematic is an effective low $Q^2$ suppression parameter. This parameter suppresses the number of interactions in the low $Q^2$ region by re-scaling the value of the Fermi-momentum used to Pauli-block CCQE interactions, we estimate a 1σ uncertainty of 30% on this parameter [4]. The effect of 1σ changes in this effective parameter is shown in figure 2.

6. Fit Results
We perform the fit in two configurations. In the first fit configuration we only fit events in the $Q^2_{QE}$ region between 0.3 and 1.2 GeV$^2$ and we fix the the $k_F$ scale parameter to the nominal value. In the second fit configuration we fit the $Q^2_{QE}$ region between 0.0 and 1.2 GeV$^2$ and let $k_F$ vary. We need the low $Q^2$ suppression that the $k_F$ parameter provides to bring our MC into agreement with our data. There are very few events with $Q^2_{QE}$ greater than 1.2 GeV$^2$ in the CCQE sample, and most of the events that are in this high $Q^2_{QE}$ region are more susceptible to the effects of mis-reconstruction. In both fit configurations the MC $Q^2_{QE}$ distribution is fit to the shape of the data $Q^2_{QE}$ distribution with the MC distribution normalized to the area of the data distribution at each fit iteration. The resulting distributions for these fit configurations are shown in 3.

We consider the effects of additional systematics by modifying the MC and then re-fitting the data. Table 1 contains a full summary of all of the systematics that we consider along with the shift in the $M_A$ parameter for each of these effects.

The preliminary MINOS results for the value of $M_A^{QE}$ with uncertainties due to the systematics effects and the fit are:

$$M_A = 1.26^{+0.12}_{-0.10}(fit)^{0.08}_{-0.12}(syst.)\, GeV \quad [0.3 < Q^2_{QE} < 1.2 GeV^2]$$

$$M_A = 1.19^{+0.09}_{-0.10}(fit)^{0.12}_{-0.14}(syst.)\, GeV \quad [0.0 < Q^2_{QE} < 1.2 GeV^2]$$
Figure 3. The left hand plots show the data, nominal MC and best fit MC for each fit configuration. The right hand plots show the corresponding plots of the ratios of the data to the MC. The top plots show the $0.3 < Q^2_{QE} < 1.2$ GeV$^2$ fit configuration. The bottom plots show the $0.0 < Q^2_{QE} < 1.2$ GeV$^2$ fit configuration. The MC histogram are normalized to the area of the data histogram.

Table 1. Change in the $M_A$ parameter due to 1σ changes in the systematic parameters.

| Systematic Effect                  | $0.3 < Q^2_{QE} < 1.2$ GeV$^2$ Fit | $0.0 < Q^2_{QE} < 1.2$ GeV$^2$ Fit |
|------------------------------------|------------------------------------|------------------------------------|
|                                    | +ve Shift (GeV)         | -ve Shift (GeV)         | +ve Shift (GeV)         | -ve Shift (GeV)         |
| CCQE Selection Criteria            | 0.018                  | 0.033                  | 0.027                  | 0.066                  |
| Hadronic Energy Offset             | 0.045                  | 0.047                  | 0.065                  | 0.075                  |
| Final State Interactions           | 0.042                  | 0.042                  | 0.079                  | 0.079                  |
| DIS Cross Section                  | 0.033                  | 0.035                  | 0.026                  | 0.025                  |
| Flux Tuning                        | 0.025                  | 0.025                  | 0.044                  | 0.044                  |
| CCQE Nuclear Effects               | 0.000                  | 0.077                  | Included in fit        |
| CCRRES Nuclear Effects             | 0.000                  | 0.021                  | 0.023                  | 0.000                  |
| Quadrature Sum                     | 0.076                  | 0.115                  | 0.120                  | 0.137                  |

7. Analysis Outlook
The preceding analysis is restricted to single track QE like events. A three selection analysis adds a two track QE like event selection along with a two track background like selection. The two track QE like selection has different kinematic properties and has greater sensitivity in the
high $Q^2$ region. The two track background like sample constrains the behavior of the nuisance parameters that control the behavior of the background to the QE sample. By performing a simultaneous fit to these three samples it becomes possible to break correlations that exist in the one track only analysis. Figure 4 plots the performance of the 0 to 1.2 GeV$^2$ one track fit to data (in red) that is presented here and compares it to a characteristic example of the three selection mock data fit. The mock data is set to the best fit values from the 0 to 1.2 GeV$^2$ fit (in blue). This mock data fit gave a best fit value for $M_A^{QE} = 1.16^{+0.04}_{-0.03}$ (fit) GeV. From this fit, and assuming the same shifts due to the effects of the systematics. We project that the error on the measured value of $M_A^{QE}$ will be +0.04/-0.03 GeV due to the fit and +0.12/-0.14 GeV due to other systematics. Thus the measurement would be dominated by these other systematics.

8. Conclusion
We have presented the MINOS preliminary results for CCQE scattering on iron at energies greater than K2K and MiniBooNE. These results show the same trend as these other experiments. The MINOS data requires that the MC include more low $Q^2$ suppression inconsistent with a basic relativistic Fermi gas nuclear model. The MINOS data also requires an increase in the relative number of event in the higher regions of $Q^2$, this is accomplished by increasing the value of $M_A$.

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