The Study of Resonance Production in the MINERνA Experiment

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1 Introduction

To simulate resonance-mediated reactions, Monte-Carlo programs use early theoretical predictions by Rein & Sehgal [1] or results from electro-production experiments, since existing data on neutrino-induced resonance production is inadequate. The theoretical and experimental picture of the resonance and transition regions is far more obscure than the quasi-elastic and DIS regions which border it. Since the event samples of present and proposed neutrino oscillation experiments fall inside this poorly-understood regime, resonant pion production is an important source of background and systematic uncertainty. This kinematic region will be carefully examined by MINERνA.

Analysis of resonance production in MINERνA[2] will focus on several experimental channels, including inclusive scattering in the resonance region ($W < 2\ \mathrm{GeV}$) and exclusive charged and neutral pion production. To date, analysis efforts have focused on MINERνA's performance for inclusive resonance production, particularly near the $\Delta(1232)$ resonance. This analysis indicates that the resolution on W is about 100 MeV in the region of the Δ, and the Q^2 resolution is better than 20%. Despite this resolution smearing, and distortion introduced by Fermi motion of bound nucleons in carbon, the Δ peak is still clearly visible in the reconstructed W distribution.

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2 Analysis of Existing Data

Inclusive electron and neutrino scattering with $W < 2$ GeV exhibits the production of resonances. Analysis so far has introduced many form factors which are then eliminated by several assumptions. The prominent resonances are $P_{33}(1232)$, $S_{11}(1535)$, $P_{11}(1440)$ and $D_{13}(1520)$. The $P_{33}(1232)$ has the largest contribution and should be understood. In electroproduction there is a dominant contribution from the magnetic dipole term. It gives an emphasis to one of the vector form factors, C_3^V, with a Q^2-dependence steeper than the dipole. The contribution of the dominant form factor C_5^A is determined by PCAC and also has a steeper Q^2-dependence than the phenomenological dipole form. It is worth pursuing this program to see if these two form factors are sufficient. The conviction is now that form factors steeper than the dipole reflect the larger size of the resonance states which are due to the mesonic cloud surrounding them. There is a simplified model that has been developed by Paschos, Sakuda and Yu[3], which accounts for existing data. The experimental results currently available have large errors and there are inconsistencies mentioned below.

One of the inconsistencies concerns the Q^2-dependence. Two older experiments at ANL[4] and BNL[5] have noticed a difference between the data and theoretical predictions in the region of small Q^2 ($Q^2 < 0.2/$ GeV^2). It appears that the same problem is revealed in newer experiments such as K2K[7] in the same region of Q^2. The BNL experiment can be fitted with the form factors used in [3] except for $Q^2 < 0.2GeV^2$ where the data falls faster than the theoretical curve (see Fig.1).

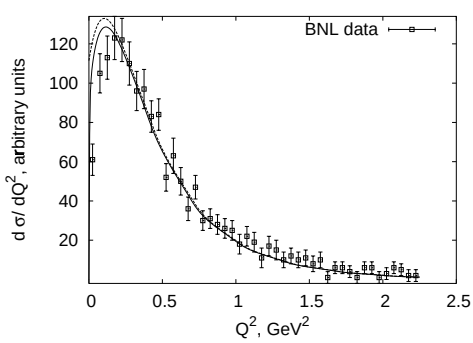

Figure 1: The cross section $d\sigma/dQ^2$ from BNL compared with fits from PSY[3]. The full lines are for the case $m_\mu = 0.105$ GeV, the dashed lines are for the approximation $m_\mu = 0$.

The muon mass, which influences the results in this region of Q^2, was neglected in previous calculations. The effect of the muon mass can be seen from the Fig.1: it reduces the cross section at small Q^2 in accordance with the experimental trends. Summarizing our results, we come to the following conclusions.

The older experiments at BNL and ANL on $d\sigma/dQ^2$ show a decrease at low Q^2 which is not understood. In addition, the dependence of the form factors on Q^2 is steeper with the ANL data. Thus, new experiments are needed to resolve this discrepancy and to determine the theoretical parameters.

The understanding of resonance production is also important for understanding the quasi-elastic process. The pion from a resonant scattering can be absorbed in the nucleus, resulting in an experimental signal that is a significant background to quasi-elastic scattering.

Other issues remain to be investigated in resonance production. In the $\Delta-$region there is an isospin-1/2 amplitude observed in electroproduction. As the higher resonances can not contribute much strength in the region of $\Delta-$dominance, this amplitude is a non-resonant background. The importance of this background increases with Q^2 to become the dominant term in deep inelastic scattering.

Nuclear corrections play a role in the absorption of pions and in charge exchange effects. The absorption is included as an overall factor and the charge-exchange changes the charge of the particle. A "rule of thumb" is the following. In a lepton-nucleus reaction on a light nucleus such as $^{16}\mathrm{O}$, the pions which have the same charge as the exchanged current are reduced by $30-40\%$, and for pions of different charge there is a slight increase. For instance, in the neutrino charge current reactions the π^+ is reduced. Half of this reduction is due to absorption and the remainder comes from change exchange of π^+ into π^0 and π^-.

MINERνA can improve the situation with precise measurements of $d\sigma/dQ^2$, $d\sigma/dW$ and integrated cross sections to further restrict the form factors.

3 Performance of MINERνA

Analysis of resonance production in MINERνA will focus on several experimental channels including inclusive scattering, (ν, μ^-) in the resonance region ($W < 2$ GeV), neutral pion production, $(\nu, \mu^-\pi^0)$ and charged pion production, $(\nu, \mu^-\pi^\pm)$. This update is focused on understanding the performance of MINERνA for inclusive resonance production, particularly near the $\Delta(1232)$ resonance.

Unlike inclusive charged lepton scattering (i.e. (e, e')), measurements of neutrino inclusive scattering with wide-band neutrino beams cannot be made by measuring only the outgoing lepton kinematics. To reconstruct the kinematics of an event (Q^2, W and y), the neutrino energy must be calculated. The is is done by estimating the hadron energy and adding it to the much more precisely known E_μ.

E_h can be estimated by tracking and identifying every particle emerging from the scattering vertex, or by summing up the dE/dx energy deposited in the detector by all the reaction products (other than the muon). Tracking will be an important technique for analysis of resonance production, as vertex event multiplicities will be low (typically $\mu+\pi+N$). However, calorimetric measurement of

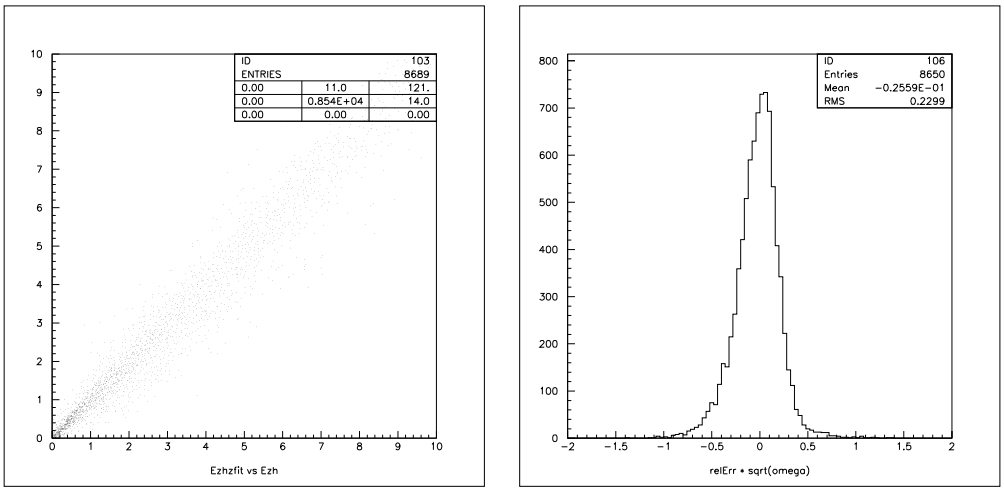

Figure 2: The left graph shows on the vertical axis the the hadronic energy E_h reconstructed from scintillator output in MINERνA vs. the true $E_h = E_\nu - E_\mu$. Right figure shows the relative deviation of the fit, $(\Delta E_h/E_h)\sqrt{E_h}$ vs. the true E_h.

E_h will be essential for inclusive resonance production in order to minimize biases in efficiency and because of the non-negligible probability for pions to interact or decay in the detector before stopping. For interacting and decaying particles, the energy not seen by active detector elements must be estimated.

In order to study the ability of MINERνA to measure E_h by calorimetry, the response of the detector was studied using the MINERνA simulation software. The NUANCE neutrino event generator was used to generate a sample of events from scattering on carbon and hydrogen which were then distributed throughout the inner detector of MINERνA. From the sample of simulated events, events where all of the hadronic fragments were contained within MINERνA were used. This tends to bias this analysis to events with lower E_h (or high multiplicity), but this is the region of interest for resonance production.

In a pure scintillator calorimeter, the total light output of the detector should be essentially proportional to E_h. (The proportionality is not unity as not all energy is reflected in dE/dx because of escaping neutrinos, the binding energy in the initial and secondary reactions and other nuclear effects such as pion absorption.) In MINERνA, there are regions of the detector with iron or lead sandwiched between scintillators. In these regions, not all of the dE/dx energy is converted to light, so the light yield in these parts of the detector must be scaled by a larger factor.

Figure 2 shows the reconstructed E_h of events vs the true E_h computed from the kinematics of the incoming and outgoing leptons. The relative deviation of the reconstructed energy from the true E_h, $\Delta E_h/E_h$, multiplied by $\sqrt{E_h}$ is shown in figure 2, giving a average resolution for reconstruction of E_h of $\frac{\Delta E_h}{E_h} = \frac{23\%}{\sqrt{E_h(\mathrm{GeV})}}$.

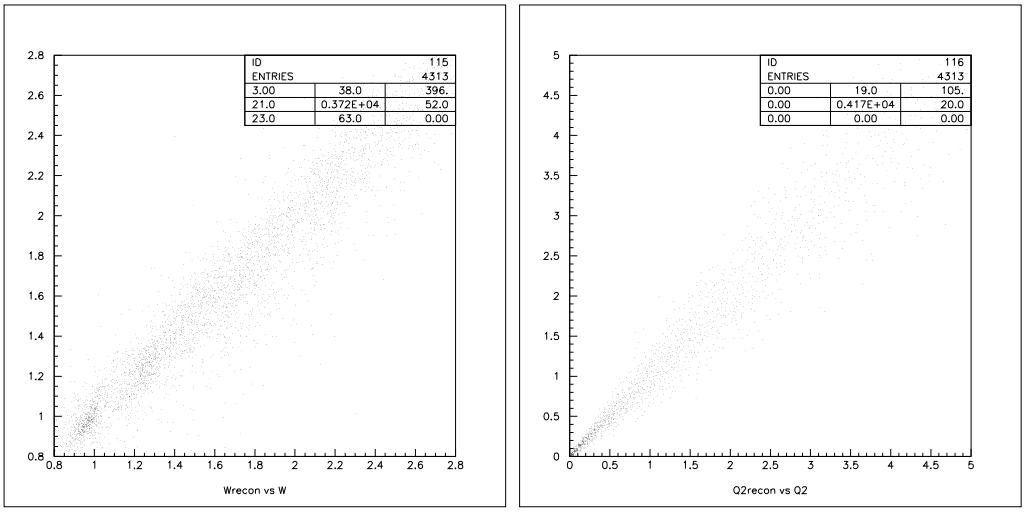

Figure 3: Correlation between true and reconstructed W (left) and Q^2 (right). Horizontal axes: true quantity, vertical axes: reconstructed.

This $1/\sqrt{E_h}$ resolution has some energy dependence and is best represented by

$$\frac{\Delta E_h}{E_h} = 4\% + \frac{18\%}{\sqrt{E_h(\mathrm{GeV})}}.$$

The kinematics of the events are reconstructed with the assumption that the muon is reconstructed with a resolution of $dP/P = 9\%$. Figure 3 shows the correlations of reconstructed W and Q^2 with the true quantities using reconstructed E_h. These show a reasonable correlation between the true and reconstructed kinematics. The resolutions of W and Q^2 obtained from the fit are shown in figure 4. The resolution of W determination is about 100 MeV in the region of the Δ and the Q^2 resolution is slightly less than $0.2\ Q^2$. The effect of this smearing is shown in figure 5 where the Δ peak is still visible in the W yield spectrum when using the reconstructed kinematics. It is important to note that the $\Delta(1232)$ distribution in W is already somewhat smeared by Fermi motion, as most of the scatterings take place on bound nucleons in carbon.

4 Conclusion

Analysis methods are being developed to exploit the tracking capability of MINERνA to refine the kinematic determination of low mulitplicity resonant events. This will permit a more accurate determination of W in the neighborhood of the Δ resonance and facilitate the the analysis of resonant events. Future studies of MINERνA performance will study the ability of the detector to make exclusive channel resonance measurements.

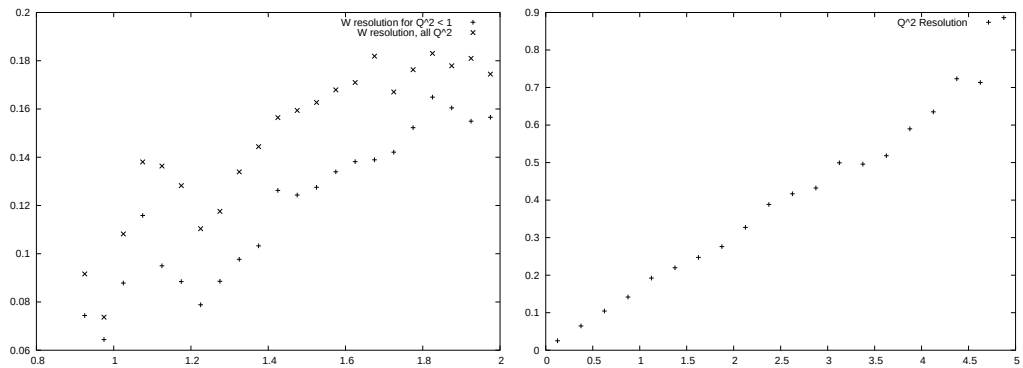

Figure 4: Resolution of W (left: units of GeV) and Q^2 (right: GeV^2) CC events fully contained within MINERνA. W resolution is shown both for all events (X symbol) and events with $Q^2 < 1\ (\mathrm{GeV}/c)^2$ (plus symbol).

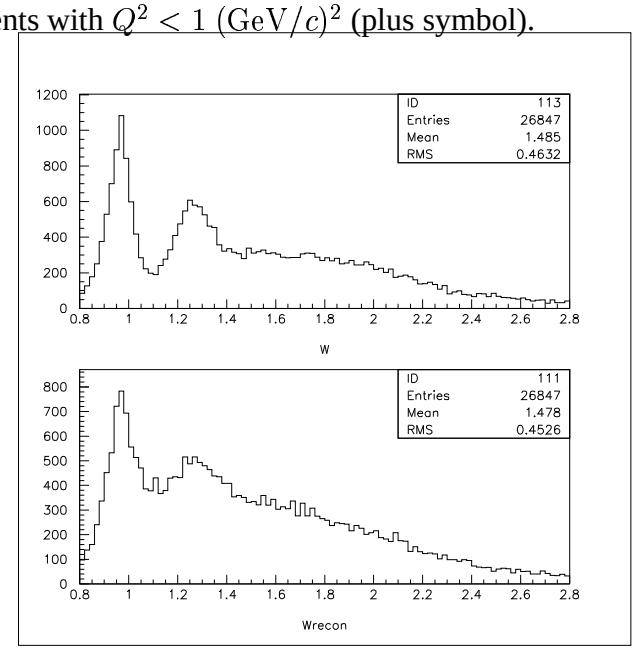

Figure 5: (Top) True W yield distribution for events with Q^2 less than $1\ (\mathrm{GeV}/c)^2$. (Bottom) Yield distribution of reconstructed W for the same Q^2 range.

References

[1] D. Rein and L. M. Sehgal, Annals Phys. **133**, 79 (1981).

[2] D. Drakoulakos *et al.* MINERνA Collaboration, arXiv:hep-ex/0405002, pgs. 49 - 61, pgs. 201 - 210.

[3] E. A. Paschos, M Sakuda, J. Y. Yu, Phys. Rev. **D69**, 014013 (2004).

[4] G. M. Radecky *et al.*, Phys. Rev. **D25** 1161 (1982).

[5] T. Kitagaki *et al.*, Phys. Rev. **D34** 2554 (1986).

[6] M. Sakuda and E.A. Paschos, Nucl. Phys. B (Proc. Suppl.) **112** 89 (2002); M. Sakuda, http://www.ps.uci.edu/ nuint/slides/Sakuda.pdf

[7] R. Gran, To be published in *Proceedings of the Third Workshop on Neutrino-Nucleus Interactions in the Few-Gev Region (NUINT04),*