Using Electron Scattering Data to Model Neutrino Quasielastic Scattering on Nuclear Targets

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Neutrino-Nucleus Interactions for Current and Next Generation Neutrino Oscillation Experiments (INT-13-54W)

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Philosophy

- Models should be able to predict W1, W2, W3 for electron scattering, charged current and neutral current processes. With these, the energy and y dependence of all predictions are well determined for all the processes.
- Models should be tested against electron scattering data to make sure that the vector contribution is properly modeled.
- Neutrino data should only be used to test the axial contribution and axial-vector interference in the model.
- I will discuss how we can use parameters extracted from electron scattering data to describe neutrino scattering cross section.

Fitting electron scattering data on Nuclear Targets
see P.E. Bosted and V. Mamyan http://arxiv.org/abs/1203.2262

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- **Resonance production on free protons:** fit hydrogen data (from other Jlab experiments)

- **Resonance production on free neutrons:** unfold data (from other experiments) on deuterium and subtract the proton and fit the free neutron data

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- **Predicted Resonance production on C12:** Fermi smear free proton and free neutron fits using Psi' scaling, multiply by EMC effect ratio. *This should the measured resonance production data on C12, provided one uses the correct EMC ratio*

- **Predicted QE production for independent nucleons on C12.** Use free nucleon form factors and smear with Psi scaling. Include Pauli suppression at very low Q^2

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- **We extract the measured Transverse Enhancement**: Take the Residuals of Data minus (sum of predicted QE for C12 *and* Fermi smeared resonance prediction for C12).

- We fit the residuals for $W^2 < 1.4$ GeV^2 to extract the TE contribution

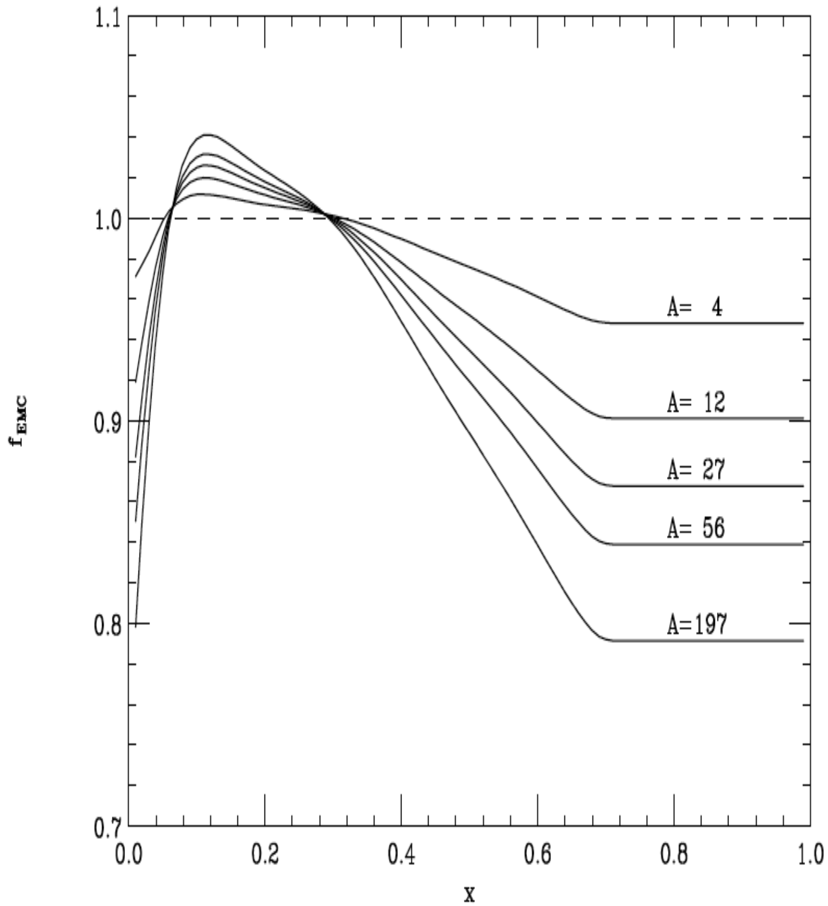
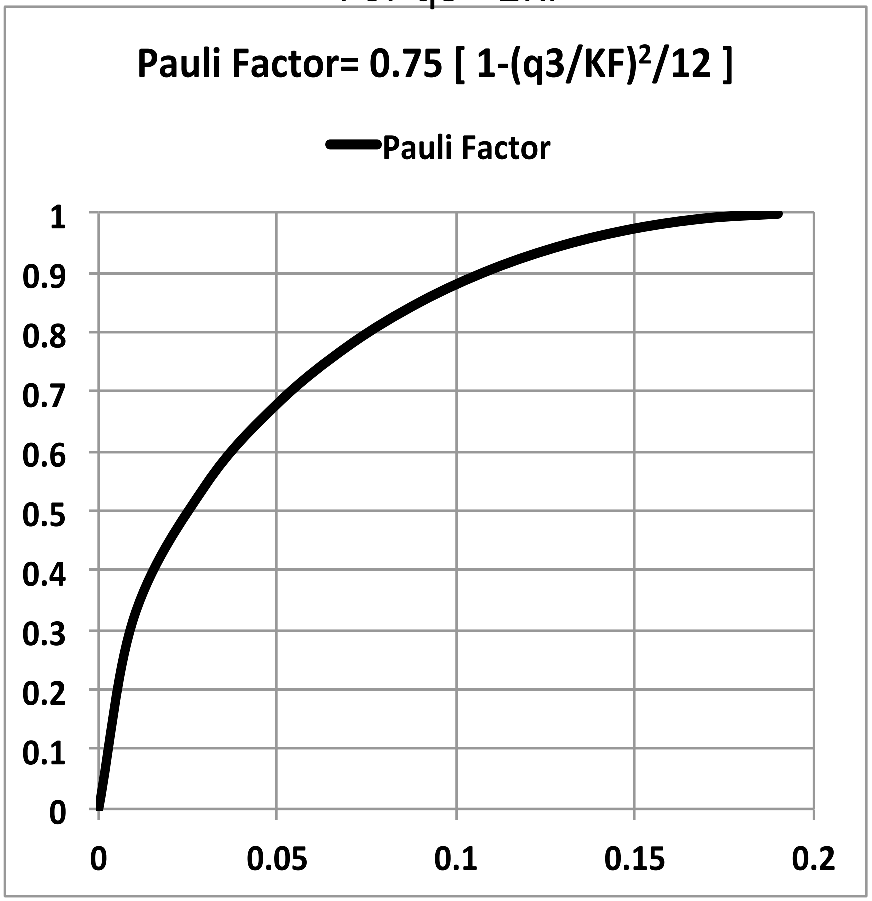


FIG. 1: Illustration of the x-dependence of the function f_{EMC} for five values of atomic number A.

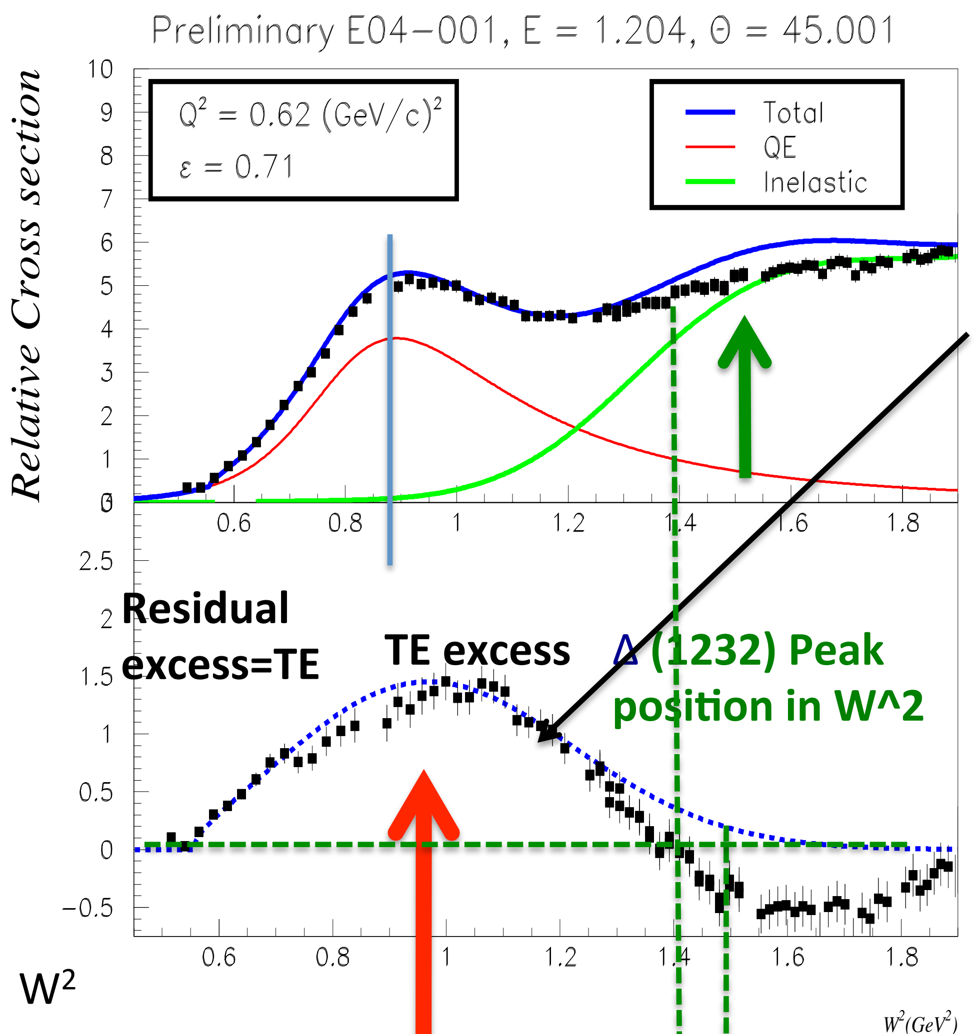
For q3< 2KF



Q^2 (GeV^2)

EMC effect in resonance region **reduces** the resonance cross section at large x. It is applied to all inelastic scattering, including resonance data.

Apply Pauli suppression to QE scattering for q3 < 2KF (q3= 3-momentum transfer)



W^2

QE peak position for TE shifted down by additional nucleon removal energy

We subtract the sum of Independent nucleon QE and Δ (1236) on C12 from the data.

1. We fit the residual excess over ν (for W^2<1.4 GeV^2. We integrated the fit up to W^2=1.5 GeV^2 and divide by the integral of the transverse contribution to the QE cross section and obtain RT (Q^2)

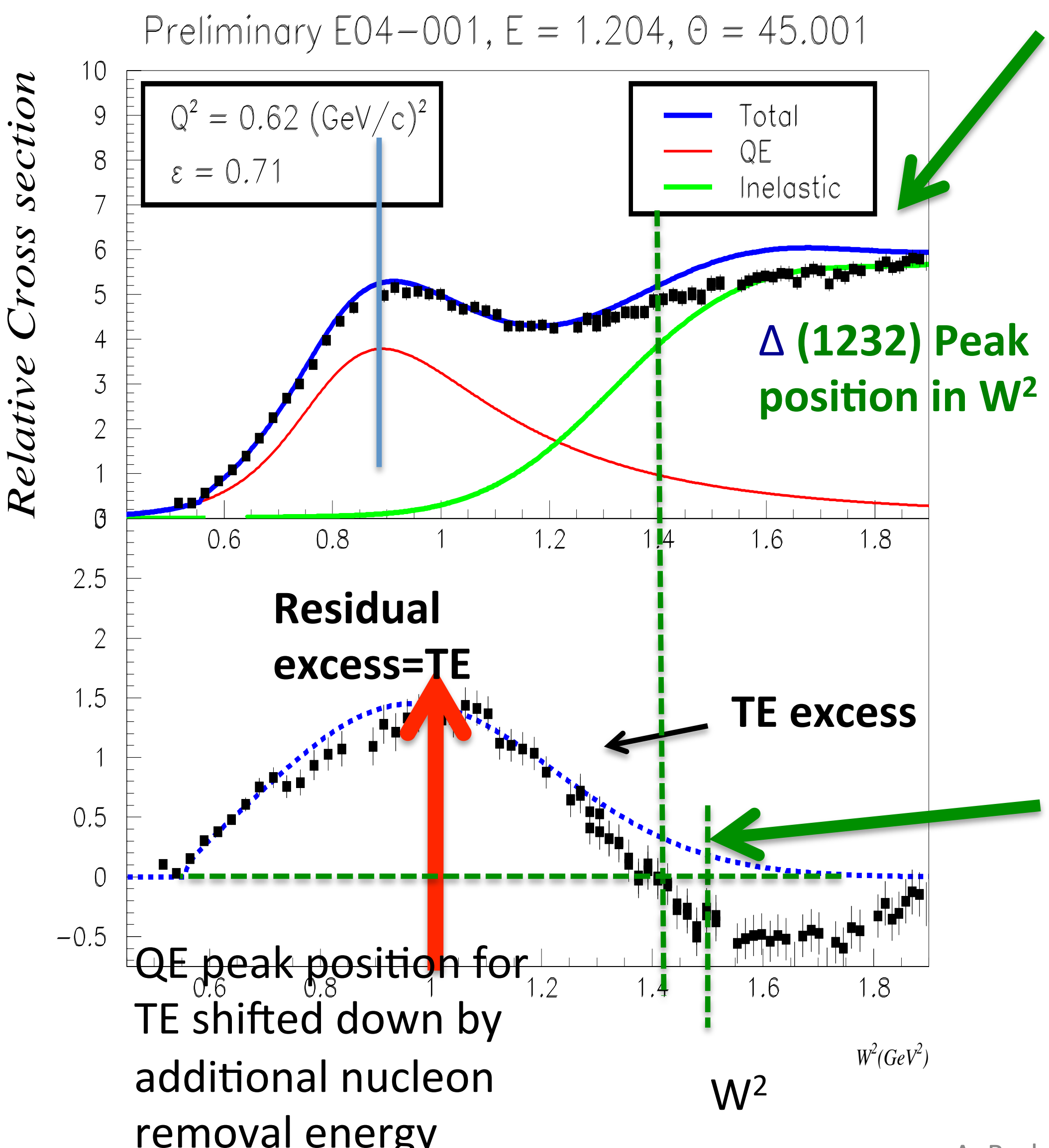
2. Extract the peak position of the fir to teh TE excess in ν (relative to the independent nucleon QE peak) vs Q^2

3. Extract the width of the fit to the residual TE excess in ν, and compare to width of independent nucleon QE peak.

In an earlier study, we only presented the integral over ν of the TE/MEC excess

A. Bodek, H. S. Budd, E. Christy

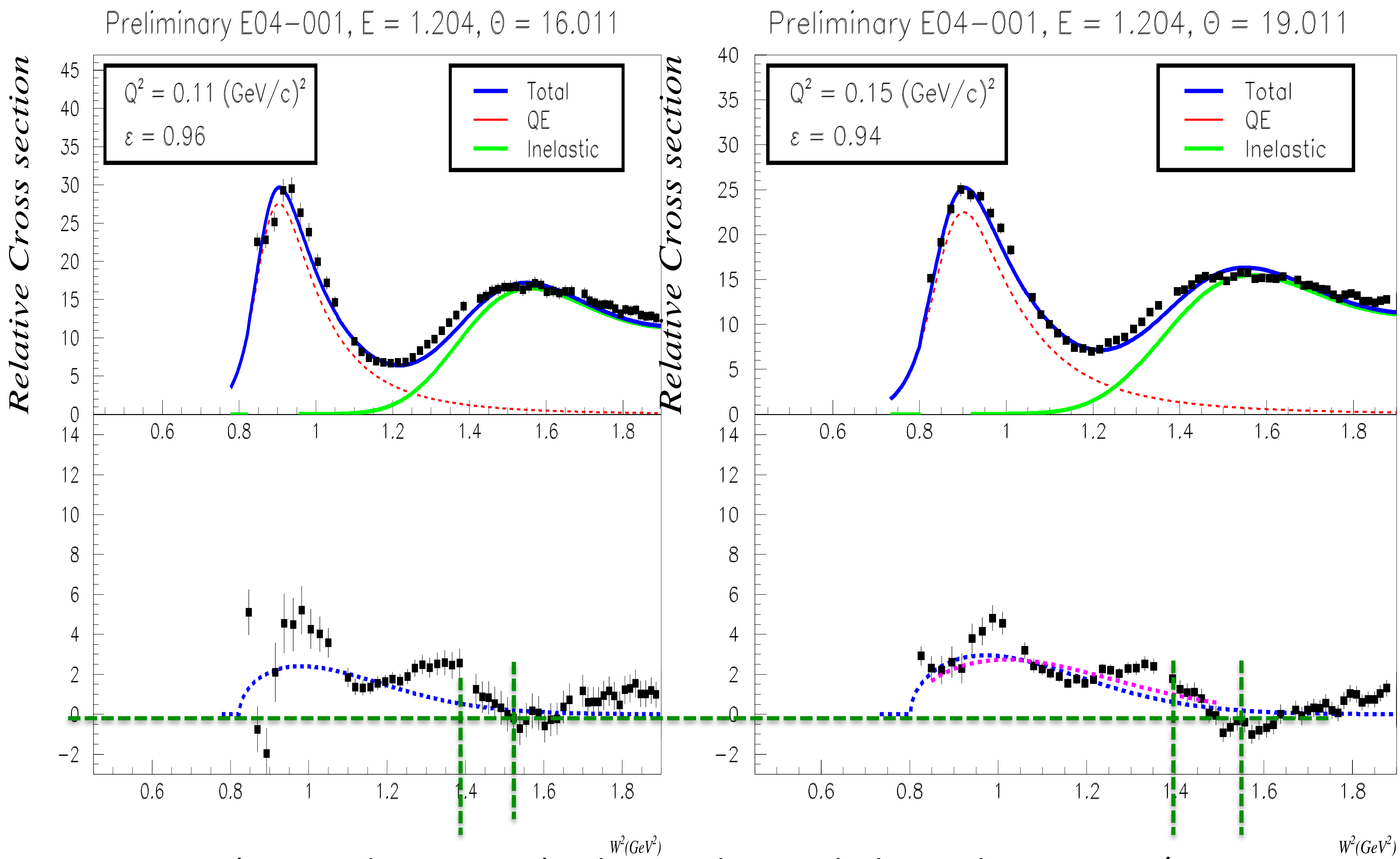
Eur.Phys.J. C71 (2011) 1726 arXiv:1106.0340 [hep-ph]



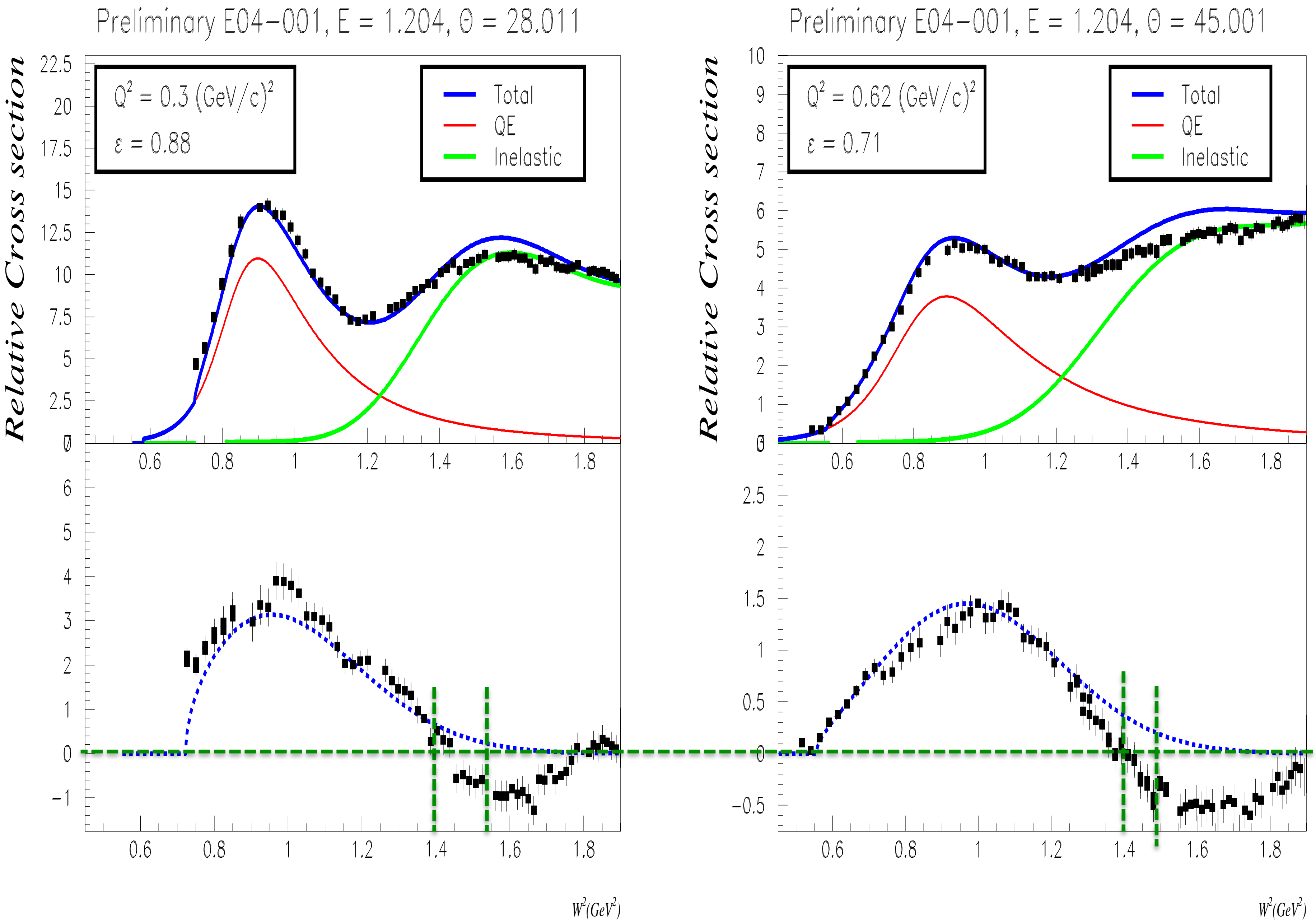
No enhancement is seen in the region of the Δ. If anything the cross section is smaller indicating a larger EMC effect. We will get back to this point later in the talk.

We plan to our data on C, D and H to study the EMC effect in the resonance region as a function of x and Q^2, or W and Q^2 and include our EMC effect correction in the next iteration of the analysis.

For now, till we get a more precise determination of the EMC effect in the resonance region, we limit the fit to the W^2 <1.4 GeV^2 region, and integrate it up to W^2 = 1.5 GeV^2. Therefore, it is a somewhat underestimated.

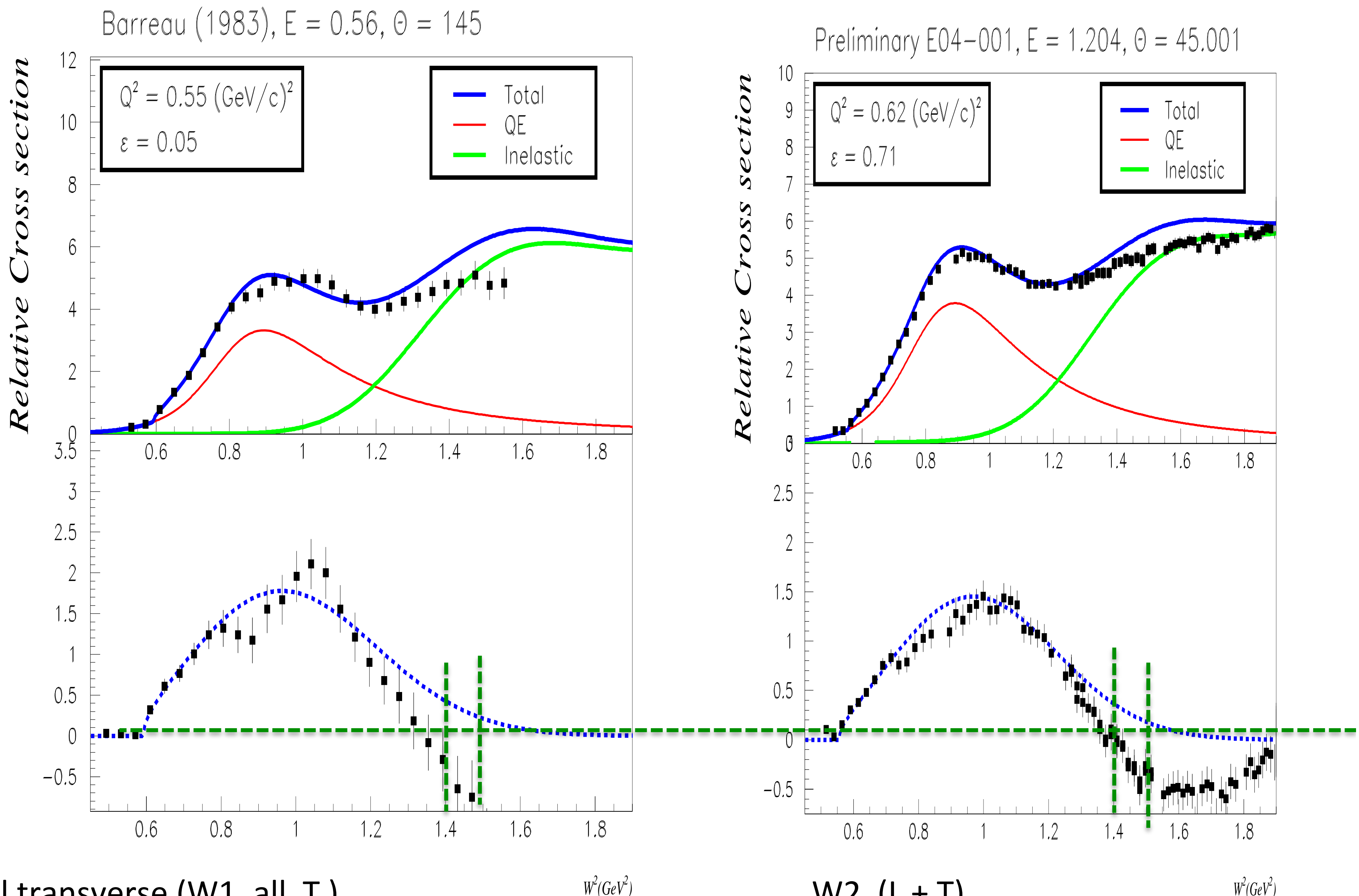


Low Q2 (0.11 and 0.15 GeV2). This overlaps with the analysis using T/L extraction from Carlson et al. The results of both analysis agree. TE is small at low Q2. Here, Delta production EMC effect works well.



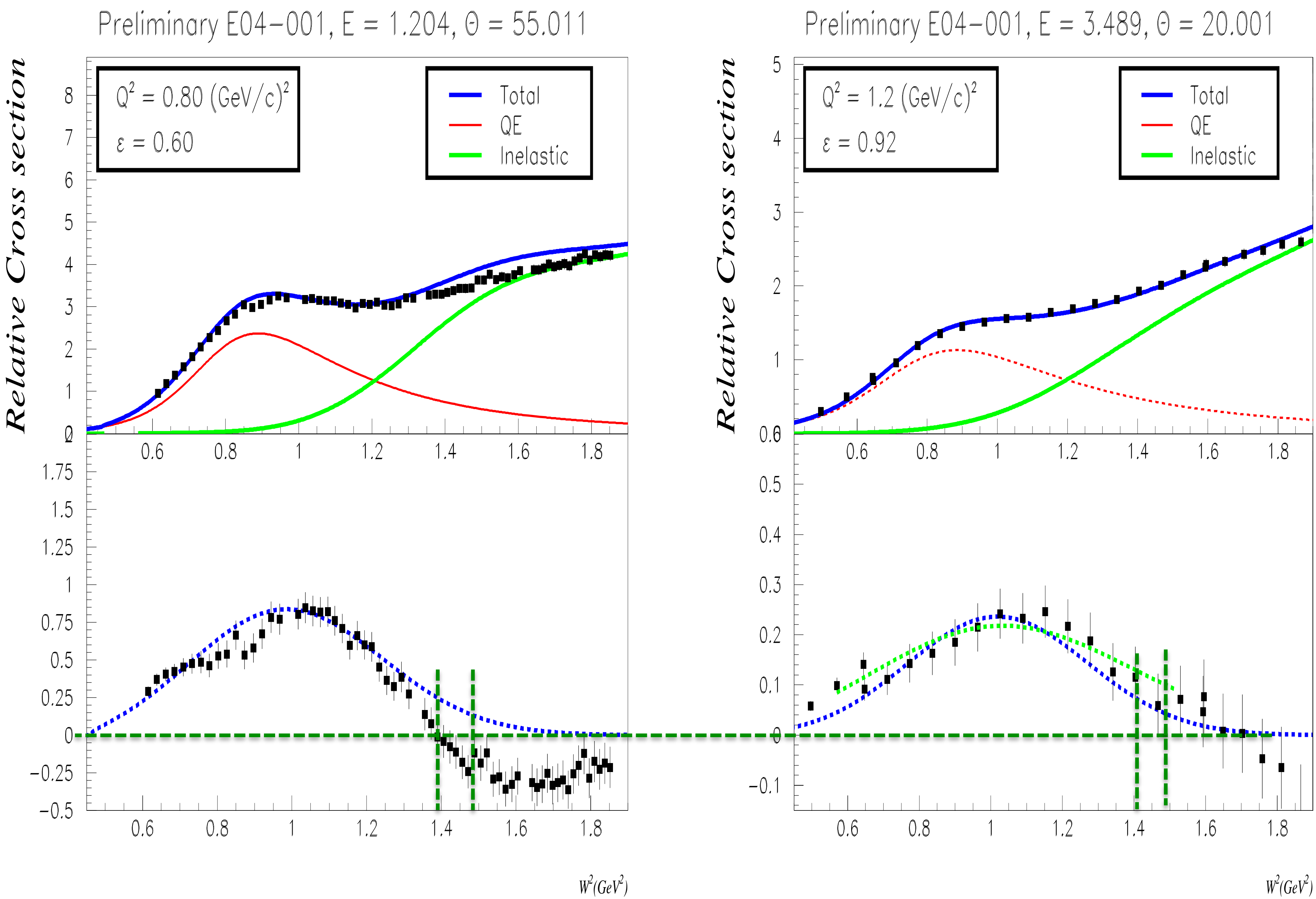
Preliminary E04−001, E = 1.204, Θ = 28.011
Relative Cross section
Q² = 0.3 (GeV/c)²
ε = 0.88
Total
QE
Inelastic
W²(GeV²)
Preliminary E04−001, E = 1.204, Θ = 45.001
Relative Cross section
Q² = 0.62 (GeV/c)²
ε = 0.71
Total
QE
Inelastic
W²(GeV²)

Same Q2=0.6 GeV2, two different epsilon

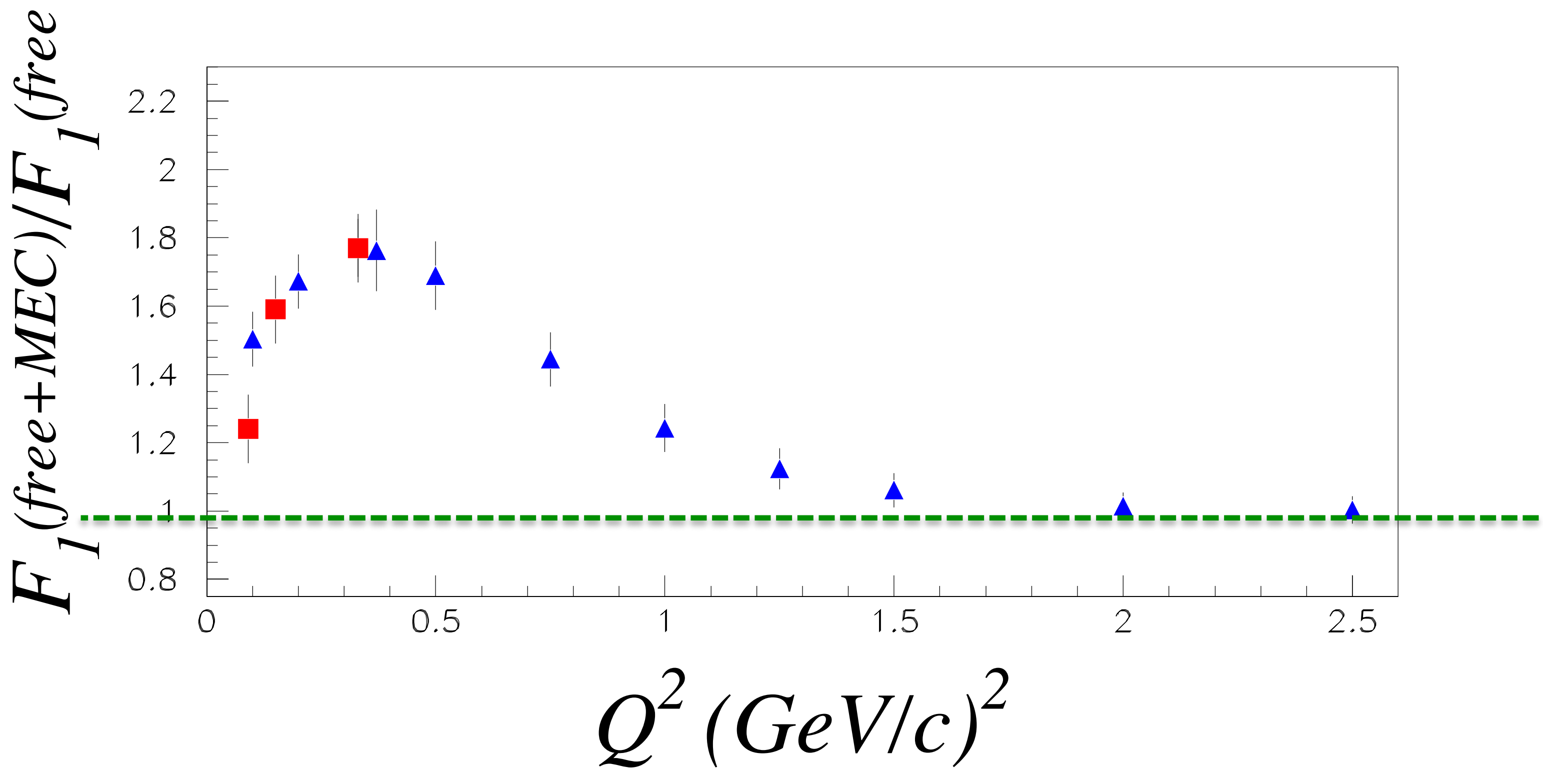


All transverse (W1, all T)

W2 (L + T)



Preliminary E04−001, E = 1.204, Θ = 55.011
Q² = 0.80 (GeV/c)²
ε = 0.60
Total
QE
Inelastic
Relative Cross section
W²(GeV²)
Preliminary E04−001, E = 3.489, Θ = 20.001
Q² = 1.2 (GeV/c)²
ε = 0.92
Total
QE
Inelastic
Relative Cross section
W²(GeV²)



Ratio of Integrated Transverse QE cross section to Predicted transverse QE cross section for free nucleons. Carlson T/L data in Red.

$\mathcal{R}_T = 1 + AQ^2e^{-Q^2/B}$ **Updated parameterization A=** 5.5064 **and B=** 0.35549

When we integrate both the TE fit and the QE psi' scaling fit, we are not as sensitive to the details of the description of the shape of the QE peak Mostly the integral). Therefore, this ratio can be used to predict the TE Q2 distribution for neutrino MC generators which use other QE models such as Fermi gas, or spectral functions.

We parameterize TE in a nucleus as a larger effective magnetic form factor of the bound nucleon.

$$G_{Mp}^{nuclear}(Q^2) = G_{Mp}(Q^2) \times \sqrt{1 + AQ^2 e^{-Q^2/B}}$$
$$G_{Mn}^{nuclear}(Q^2) = G_{Mn}(Q^2) \times \sqrt{1 + AQ^2 e^{-Q^2/B}}.$$

This prescription assumes that there is no enhancement in longitudinal scattering, or in the axial contribution in neutrino scattering.

Longitudinal (L) – scattering from charge*. Charge is conserved, Coulomb sum rule is found to be valid in electron scattering. Since no enhancement is seen in the longitudinal scattering it implies that the charge distribution of bound nucleons is not changed in a nucleus.*

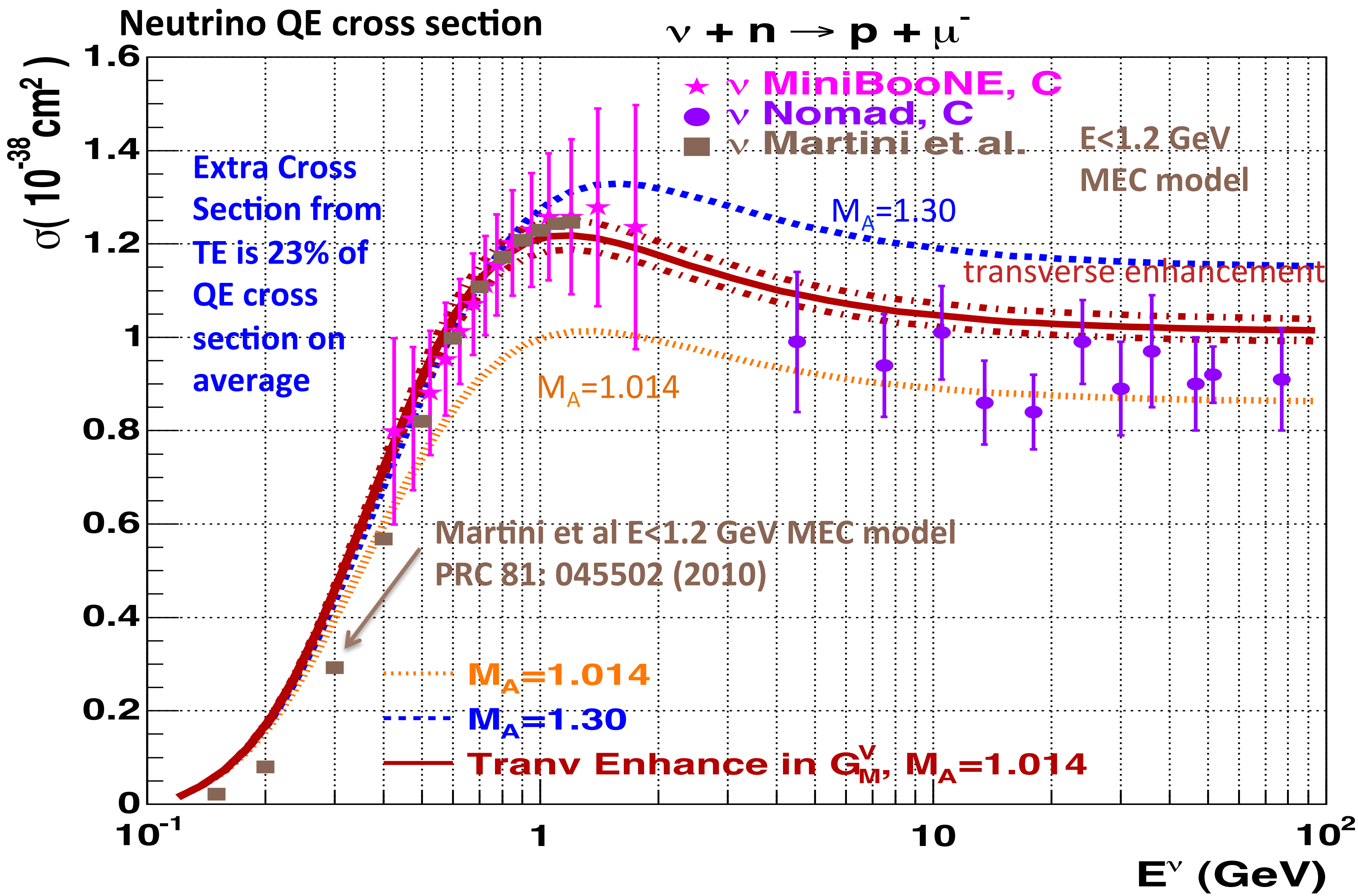
Transverse (T) – Scattering from currents**, orbital angular momentum and Dirac and anomalous magnetic moments***. These are not conserved (e.g. Meson exchange currents)*

Axial current is partially conserved*, so we assume that axial form factor is not modified in a nucleus.*

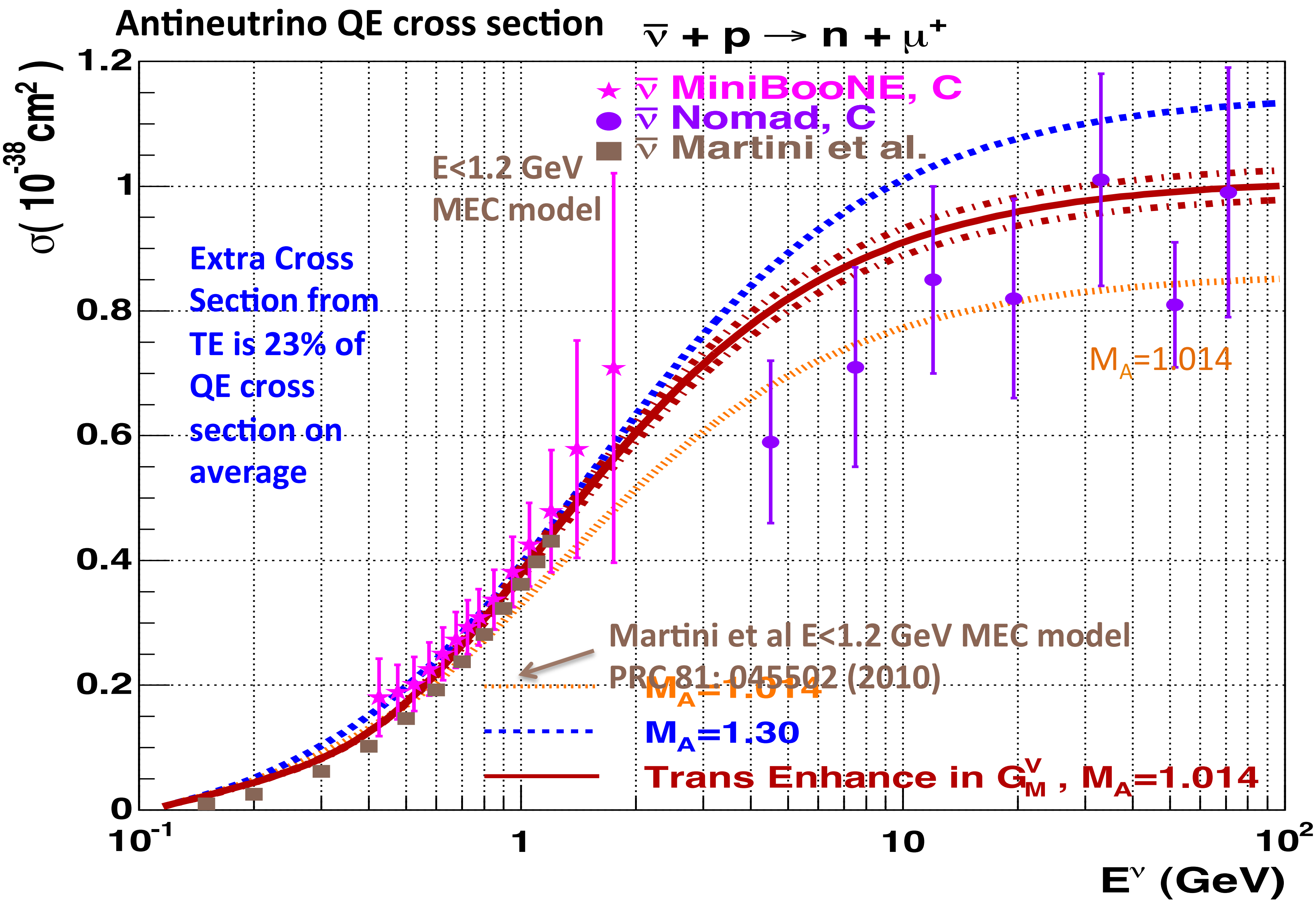
The above prescription implies that the vector amplitudes from MEC/TEC interfere with axial current in the non-TE Transverse component

Predicting neutrino QE cross sections on nuclear target from electron scattering data

- Use free nucleon vector form factors.
- Use free nucleon axial form factor (M_A=1.014 GeV)
- Model transverse enhancement as an increase in the magnetic form factor of bound nucleons (e.g. from additional currents, but the source is not really relevant in this approach).

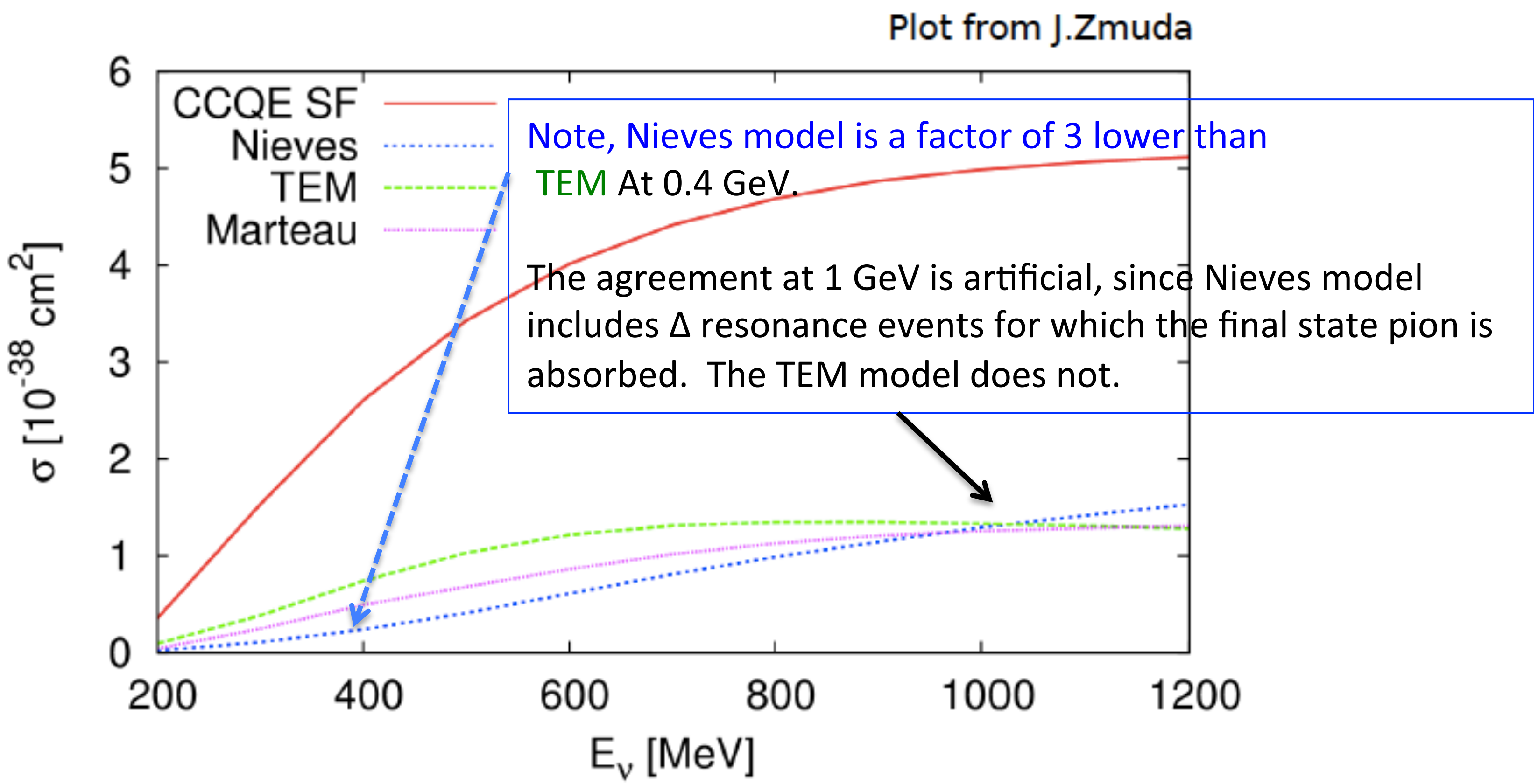


The prediction for the total QE cross section is only sensitive to the integral of the QE and TE contributions. It is not sensitive to modeling the shape of the distribution in ν .



The prediction for the total QE cross section is only sensitive to the integral of the QE and TE contributions. Therefore, It is not sensitive to modeling the distribution in ν .

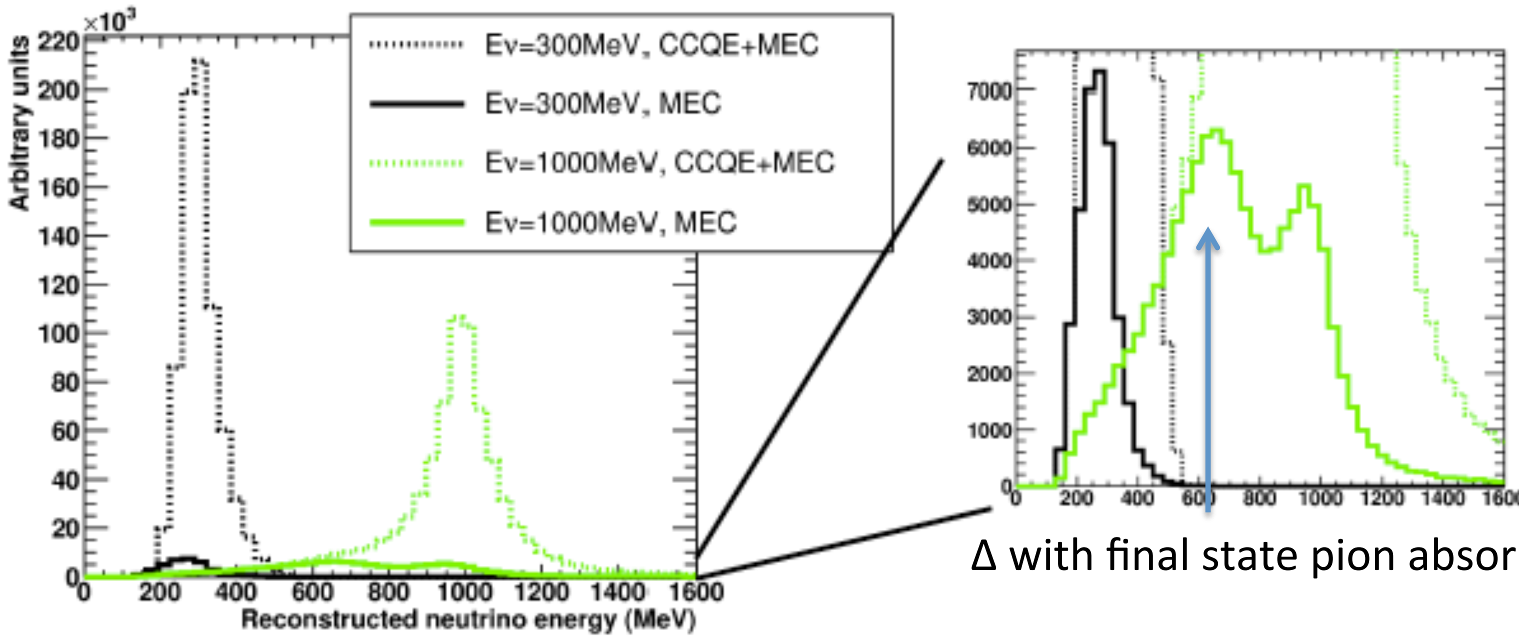
Comparison of prediction from TEM to other models for mult-inucleon process



Plot from Peter Sinclair, Imperial College, T2K

Plot from Peter Sinclair, Imperial College, T2K. Nieves model

Neutrino energy reconstructed under the QE assumptions

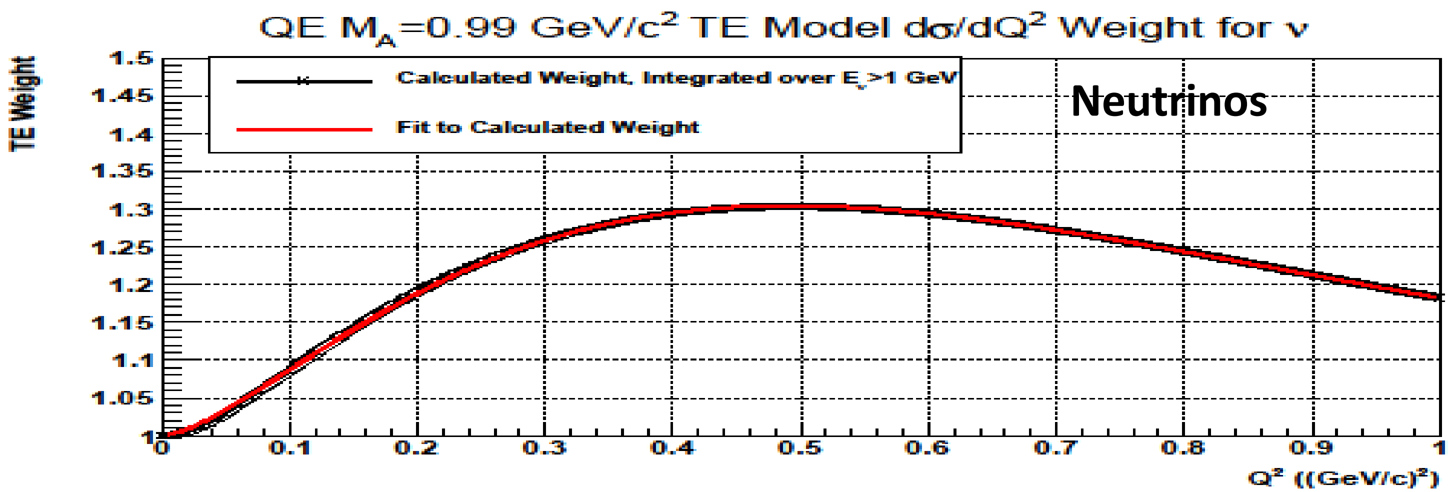


Δ with final state pion absorption

Nieves model **includes Δ production** for which the pion is absorbed in the nucleus.
The **TEM model does not** (All Δ production on C12 is included in the Δ production model)

Beware of double counting pion-less Δ production **in neutrino MC when implementing some of the multi-nucleon models. (not for TEM). In practice, all neutrino MC generators already include pion-less** Δ production **as part of the general simulation of** Δ production.
So is not really an issue since it is included in the MC one way or another.

Reweighting QE MC events to include the TE (Q^2) contribution is simple



High energy experiments such as NOMAD will get a smaller MA because they fit over a much larger range in Q2.

Ratio of neutrino QE $d\sigma_{QE}/dQ^2$ with and without TE (for neutrino energies>2 GeV)

Extra Cross Section from TE is 23% of QE cross section on average. (30% at Q^2=0.5 GeV^2)

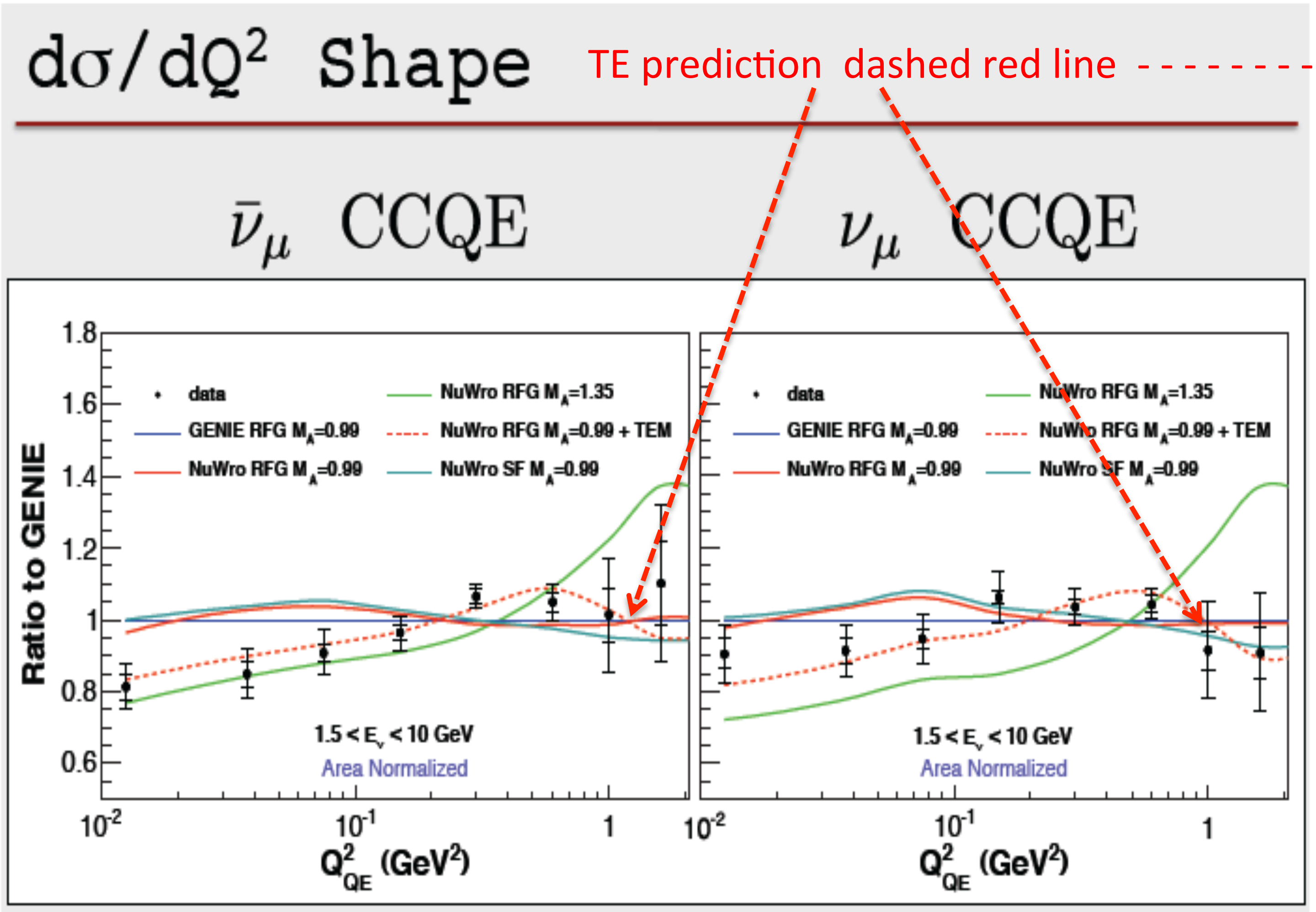
For neutrino energies greater than 2 GeV, the same function describes both neutrinos and antineutrinos (Functional form below is from Ulascan Sarica BS Thesis U of R, 2013).

We can use this funct
change in GENIE).

$$R_{\nu}^{QE-TE} = 1+\left[4.51156\cdot\left(Q^2\right)^{1.57538}\cdot exp\left(-3.20978\cdot Q^2\right)\right]$$
$$R_{\bar{\nu}}^{QE-TE} = 1+\left[4.52711\cdot\left(Q^2\right)^{1.57751}\cdot exp\left(-3.21362\cdot Q^2\right)\right] \quad (2.3)$$

Different functions should to be used for neutrino energies< 2.5 GeV (different for neutrinos and antineutrinos)

1. Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at *Ev*~3.5 GeV MINERvA Collaboration . May 9, 2013 e-Print: arXiv:1305.2243
2. Measurement of Muon Antineutrino Quasi-Elastic Scattering on a Hydrocarbon Target at *Ev*~3.5 GeV MINERvA Collaboration May 9, 2013 arXiv:1305.2234



Note for high energies, the the Q^2 distribution does not depend on modeling the QE or TE contribution in ν since the width of the QE peak is much smaller that the neutrino energy

Investigation of peak and width of QE and TE contributions in ν

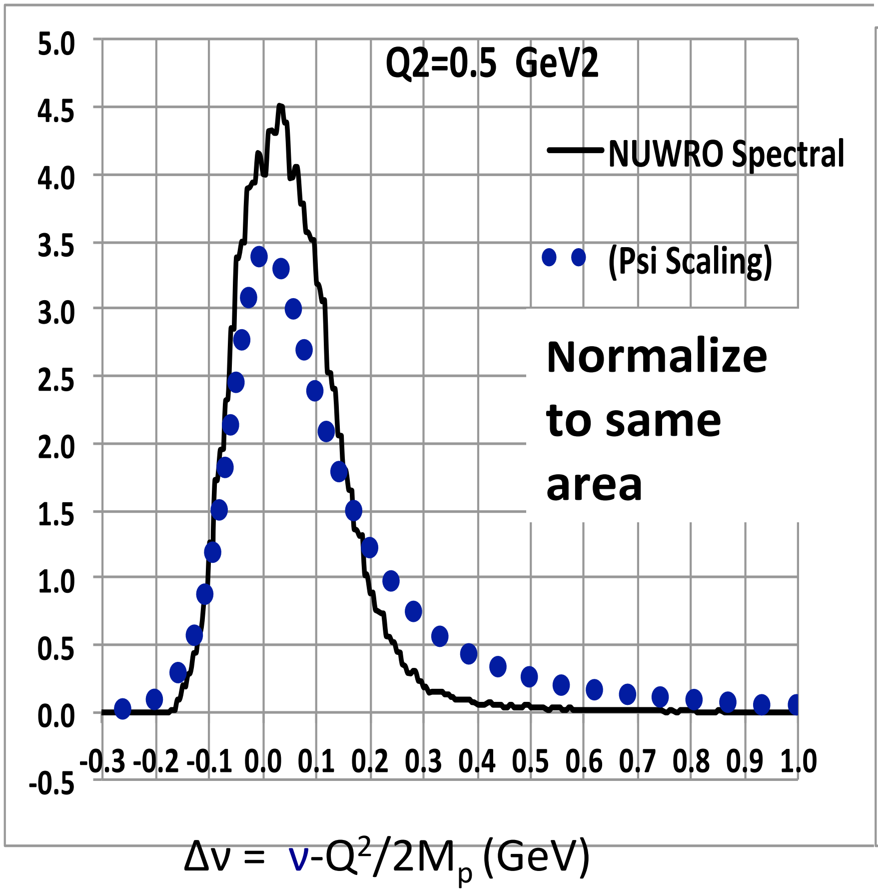
- Modeling TE as an effective increase in the magnetic form factor of bound nucleons assumes that the QE independent nucleon component and the TE/MEC component have the same shape in final state W (or equivalently energy transfer ν).

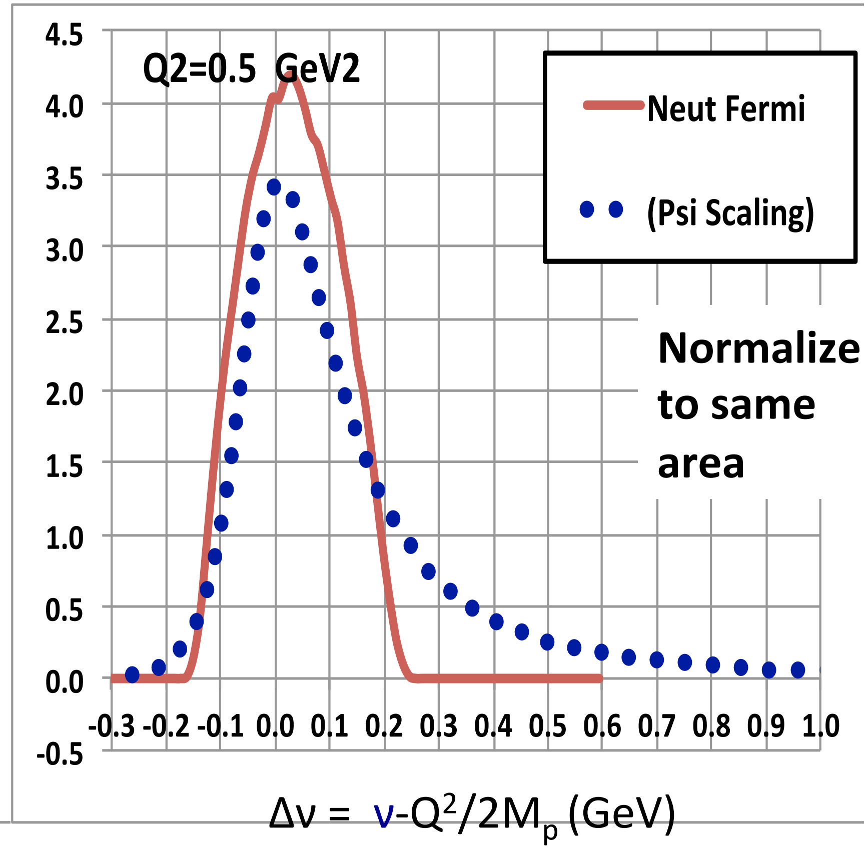
- Consequently we proceed to compare the shapes and peak positions of the QE and TE components. This comparison is preliminary since we will repeat again to include a better model for the EMC effect for the Delta.

- Note: The QE contribution is 80% of the cross section. The TE contribution is 20% of the cross section.

- Therefore, it is more important to get the correct shape of the QE contribution first, and include the difference in shape between QE and TE later. Much of the difference in the shape between QE data and MC models could be from mis-modeling of the shape of the independent nucleon contribution. In our method, the sum of the shape of QE and TE is conserved, so the shape of the TE requires a good prediction for the shape of QE.

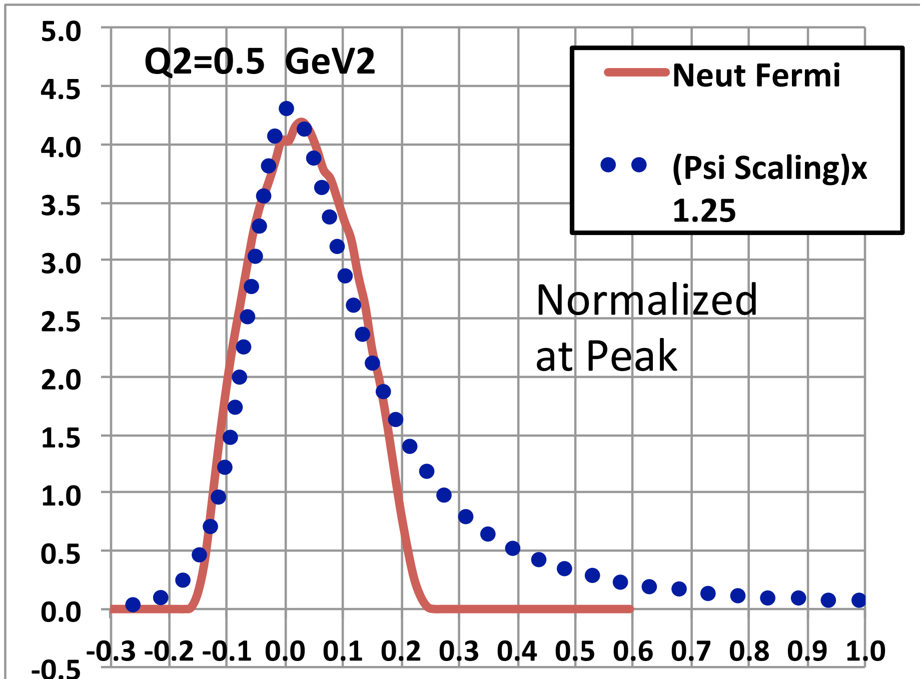
Comparison of Spectral function calculations to Psi scaling fits to electron scattering data

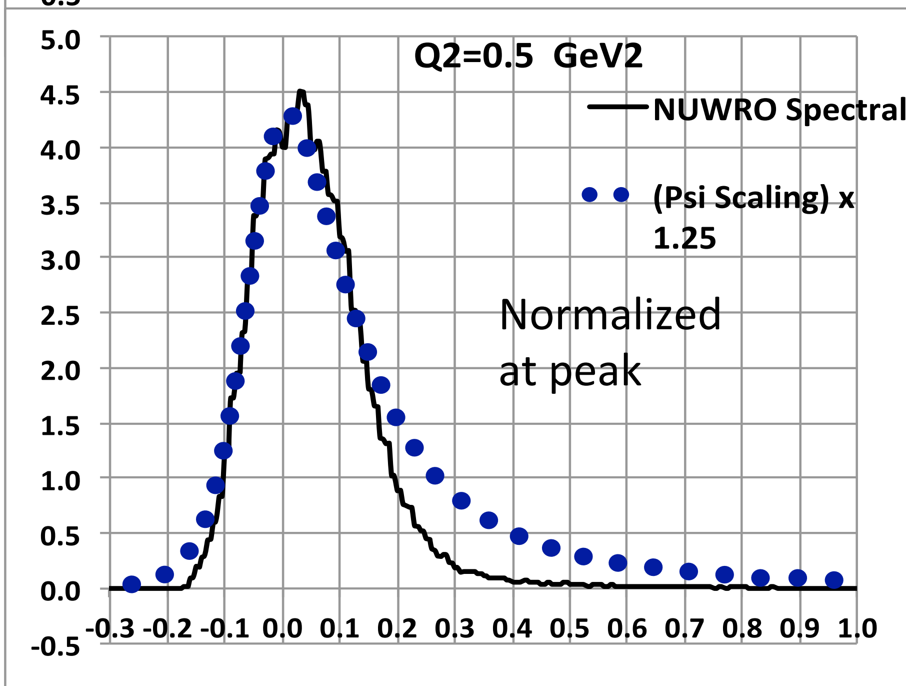




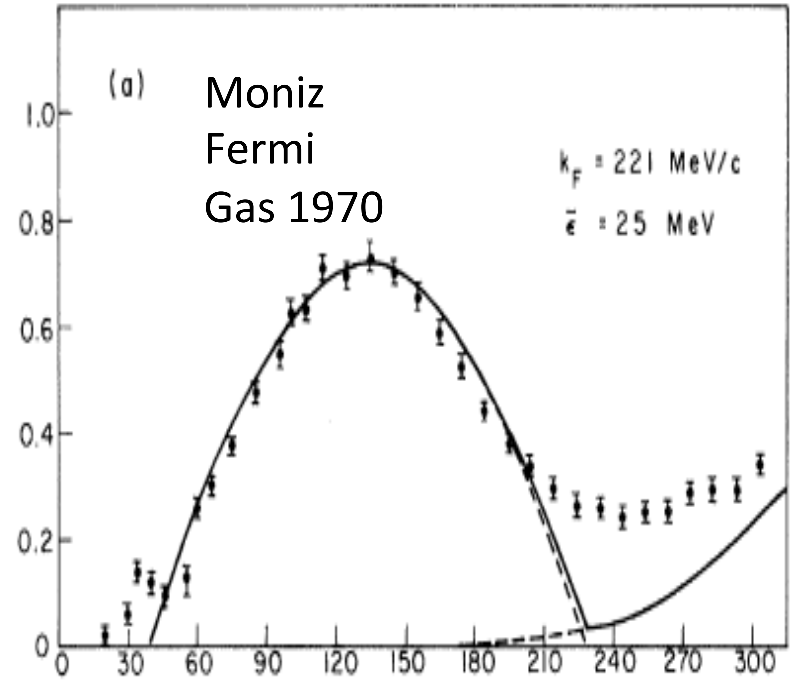
If we compare the shape or the QE peak at fixed Q2, we should get the same shape in electron scattering and neutrino scattering.

The Psi' scaling curve has a larger tail than the Fermi Gas nor Benhar Fantoni spectral for QE scattering. This difference needs to be understood.
(Increasing the high momentum components in the Spectral Function would reduce some of the difference).



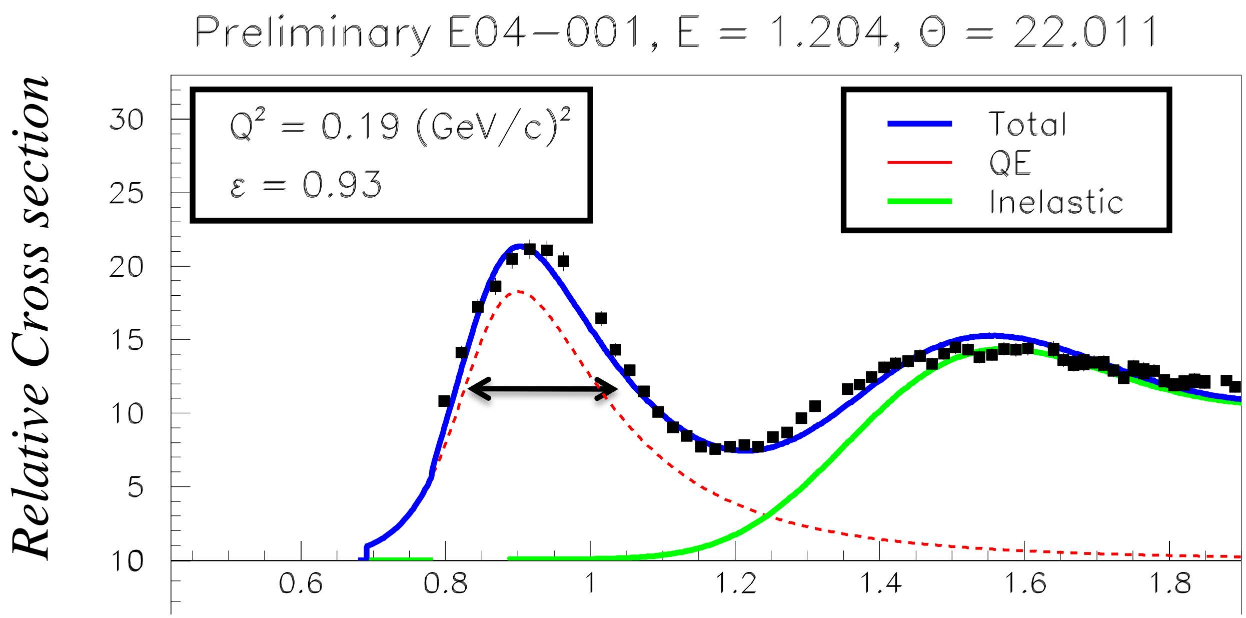


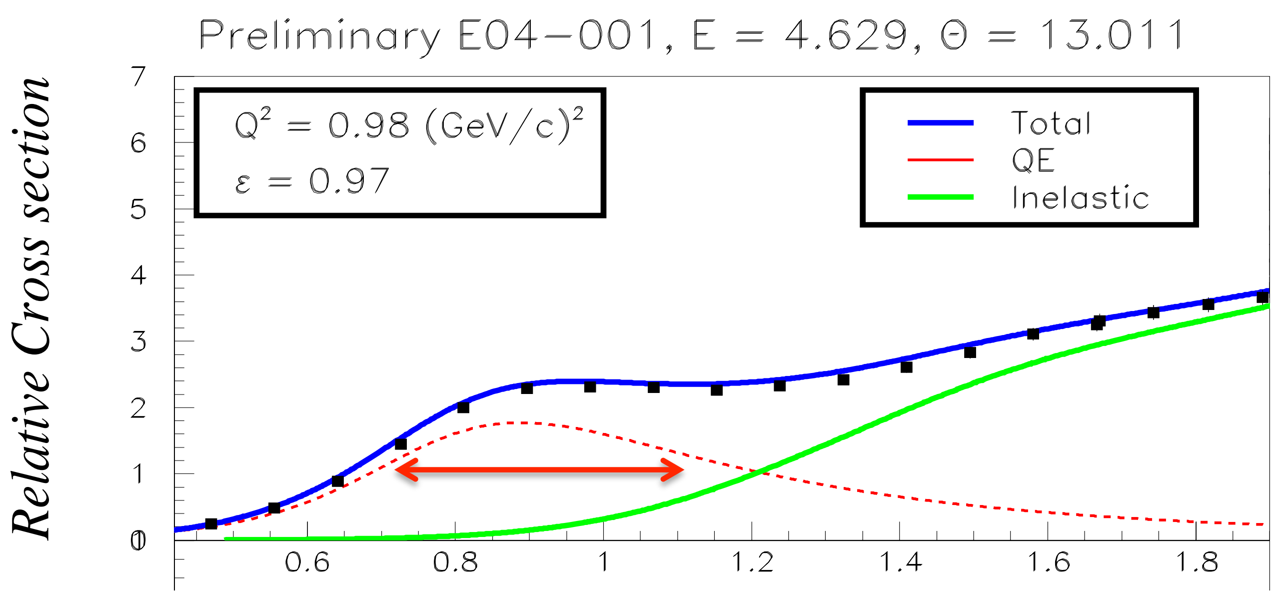
$\Delta\nu = \nu - Q^2/2M_p$ (GeV)



Here models are normalized **in the peak region**.

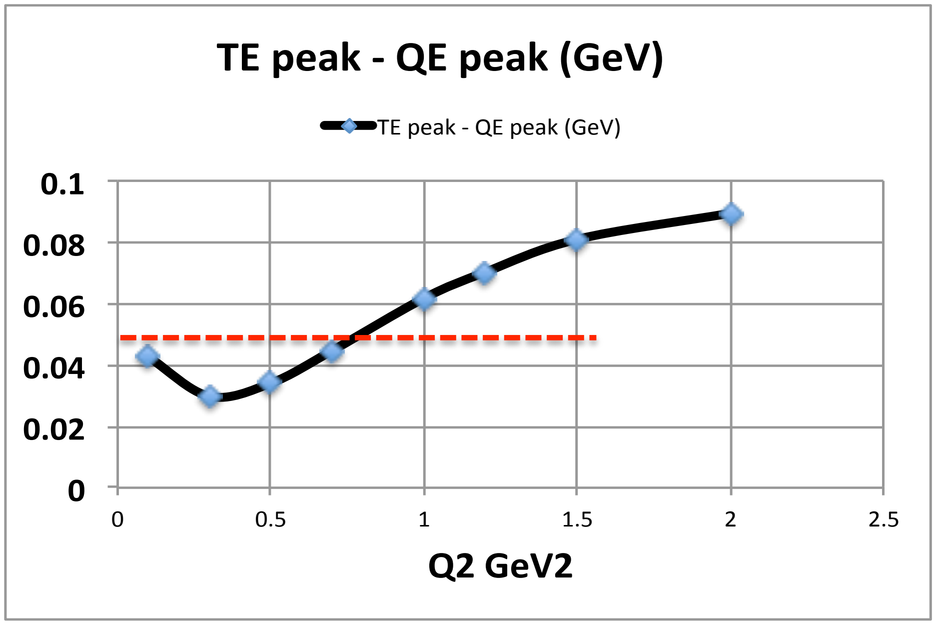
(The experts in this workshop may be able to comment on whether a spectral function approach and the Psi; scaling approach should yield the same predicted shape for the QE peak).

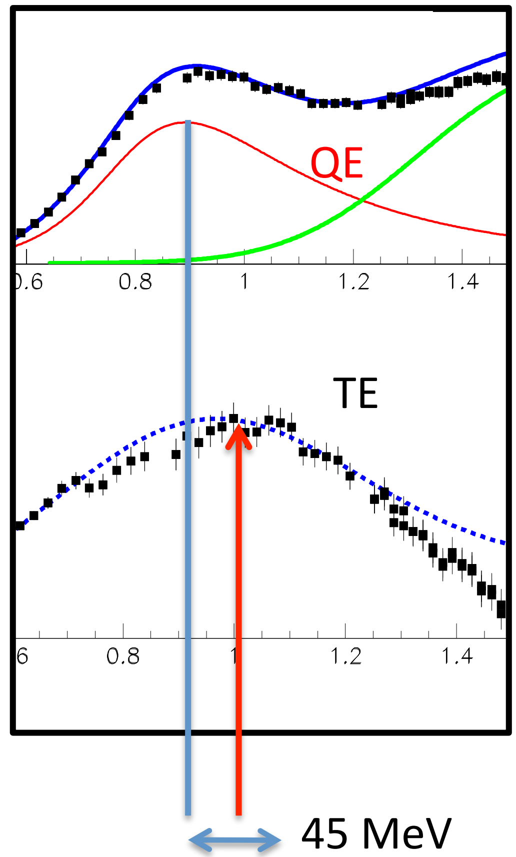




RMS width of QE is expected to increase linearly with the three momentum transfer q_3

Comparison of peak position of TE and QE fits

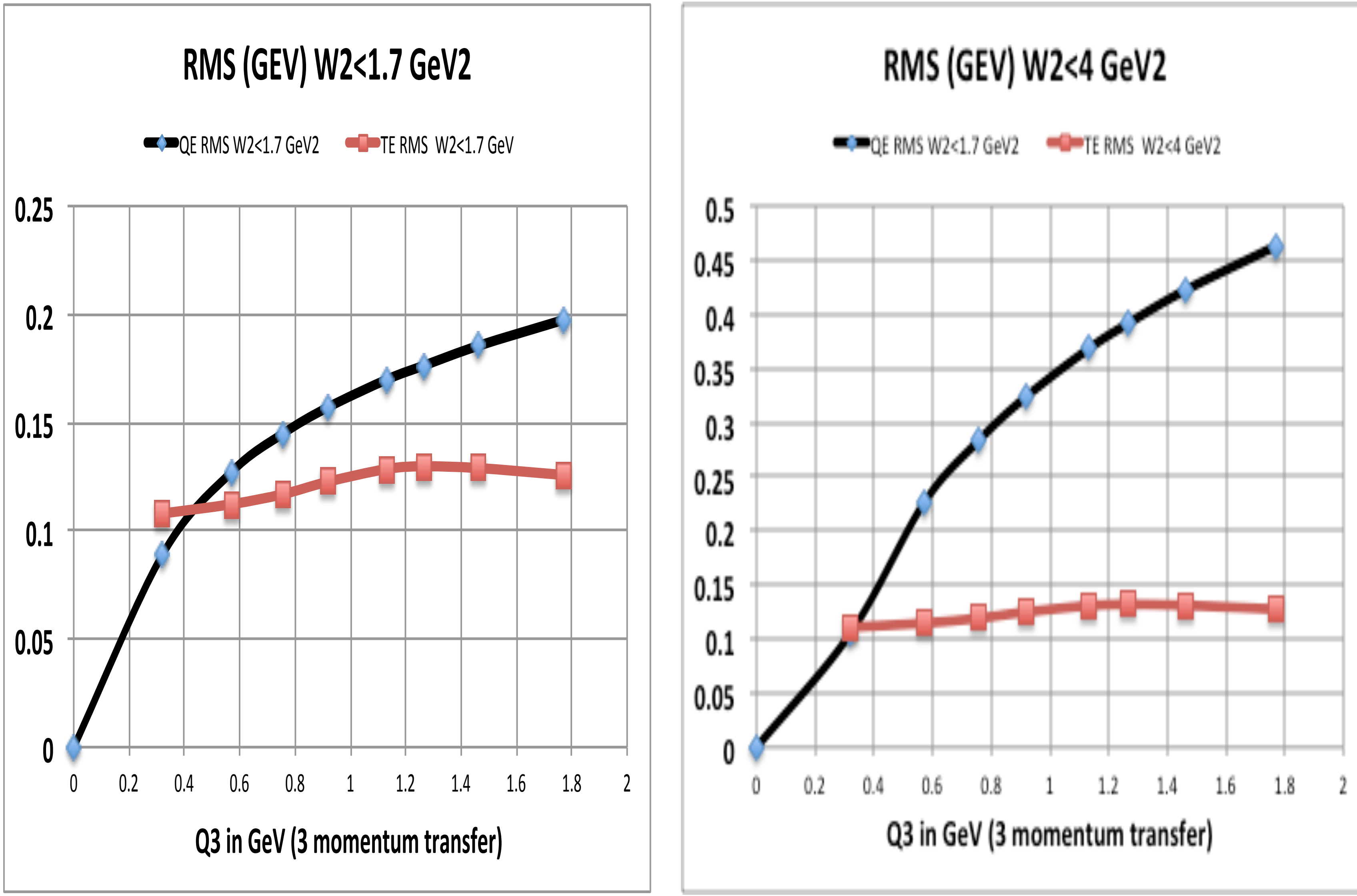




•Difference is about 45 MeV for $0 < Q^2 < 1$ GeV^2.

•TE peak is about 50 MeV higher in hadronic final state energy ν than the independent nucleon QE peak**. It is predominantly in the region of the QE peak**

Comparison of RMS width of TE and QE fits



RMS of TE is about 0.125 MeV

RMS of QE increases Linearly with Q3

Modeling 2 nucleon final state for TE

TE/MEC is a two nucleon process. Lets call this a quasideuteron with mass 2M.

- For a single nucleon $(W_{1N})^2 = M^2 + 2\ M\ \nu - Q^2$ $(x_{P\text{-}max} \approx 1)$
- For a two nucleon $(W_{2N})^2 = 4M^2 + 4\ M\ \nu - Q^2$ $(x_{P\text{-}max} \approx 2$, or $x_{D\text{-}max} \approx 1)$

So there is not much scattering for $x_P > 2$ for a two nucleon process ($W_{2N} = 2M$)

We have measured the Q^2 and ν dependence of ME/TE.Therefore, the energy of the final state muon muon and final state hadronic energy for MEC/TE events are known.

The only question is how to allocate the energy between the two final state nucleon.

We also know the total energy and mass of of the 2 nucleon system $(W_{2N})^{2.}$
My proposal for modeling the sharing of the energy between the two nucleons is
To assume that the angular distribution of the two nucleons in the W_{2N} center of mass is uniform.

Since both nucleons undergo subsequent final state interaction with the rest of the nucleus, the post FSI final state should not be that sensitive to this assumption.

Generating QE and TE events in MC.

1. Use free nucleon form factors.

2. Momentum distributions and spectral functions for QE events: Need to model the correct Q^2, ν distributions for the final muon and final state hadrons (80% of the events)

Neither Fermi gas nor Benhar Fantoni Spectral function predictions agree with the shape of psi scaling QE peak in the tails of the distribution. ***This needs to be understood.***

3 Including the TE contribution as a function of Q^2 (20% of the events):

(a) We can reweight MC events by the ratio of TE to QE cross sections as a function of Q^2 to model the Q^2 dependence of the integrated TE contribution.

(b) We can generate the energy distributions for the final muon and final state hadrons for the TE contribution (we measured the the peak position and RMS). We are finalizing the extraction of the RMS and shape of the TE distribution. The TE distributions are truncated around x=2. However, this shape is sensitive to the assumed shape for the independent nucleon QE distribution. (Back to item 2)

4. A simple prescription for sharing the energy between the two nucleon final state can be implemented (uniform angular distribution in the two nucleon final state center of mass).

What is left to be done

- Use the data to extract the EMC effect in the resonance region as a function of x and Q^2 (also topic of interest to the neutrino community).

- The EMC effect in the region of the Delta is larger than the fit for the SLAC DIS data. Getting it right will improve the shape of the extracted TE/MEC for large energy transfers (and result in a larger extracted width.

- Refine the functional form for TE/MEC (currently a modified Gaussian with a threshold near x = 2) and redo the entire analysis with the improved modeling of the EMC effect in the resonance region.

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- Another issue, is there a spectral Function/momentum distribution that can be used in neutrino MC generator that agrees with wider shape of the prediction of the psi' scaling independent nucleon QE peak. Should we modify the momentum distributions, or the Psi scaling curves in the TEM analysis (or both).