Transverse Enhancement and Meson Exchange Current Contributions to Quasielastic (QE) Neutrino Scattering on Nuclear Targets

Arie Bodek, Howard Budd

University of Rochester

M. Eric Christy, Thir Narayan Gautam

Hampton University

WIN2013, Natal, Brazil September 16-21, 2013

Thursday Sept. 19, 2013 **10:22** to **10:39 AM.**

Abstract 53 Working Group 2 (Neutrino)

Jupiter Collaboration (Jlab E04-001)
A. Bodek, Cynthia Keppel, Eric Christy
Spokespersons

- We have measured electron scattering cross sections on nucleon and nuclear targets in the few GeV region in 2004 and 2007

- We use these new measurements in conjunction *with all previous electron scattering data to* extract the vector contributions (form factors, structure functions, QE nuclear response functions, etc.) to neutrino cross sections on protons, neutrons and nuclear targets in the few GeV region.

- Jupiter is Complementary to the MINERvA neutrino experiment

Abstract of this talk (TE in QE scattering on nuclear targets)

- We use quasielastic (QE) electron scattering data on nuclear target to parametrize the enhancement to the transverse response functions in nuclear targets (TE). This enhancement has been attributed to meson exchange currents in nuclei.

- Regardless of its origin, the enhancement can be experimentally investigated in detail using electron scattering data. The overall magnitude can be parameterized as Q^2 dependent enhancement of the magnetic form factors of bound nucleons.

- In this paper, we provide an updated more precise parametrization of the overall magnitude of the transverse enhancement as a function of Q^2. The parameterization is in good agreement with recent measurements of the Q^2 distributions of neutrino charged current QE events in the MiniBooNE and MINERvA experiments.

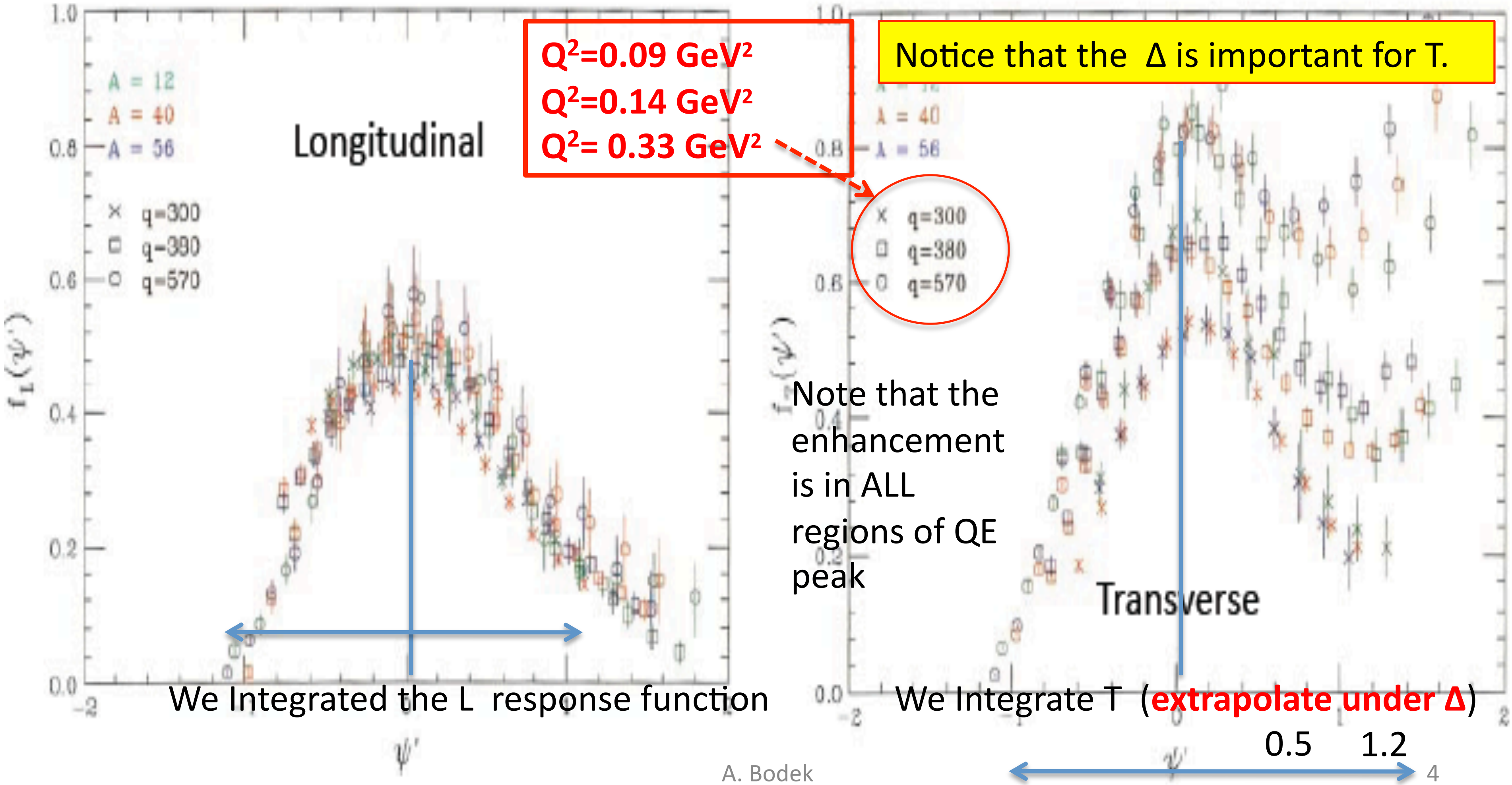
- We also compare the peak position and width of the TE contribution to that of the quasielastic contribution without TE.

Donnelly and Sick Phys. Rev. **C60**, 065502 (1999) J. Carson et a. Phys. Rev. C 65 024002 (2002)

Response functions (assume free nucleon form factors, and remove their Q2 dependence)

Transverse is enhanced by a Q2 dependent factor R_T

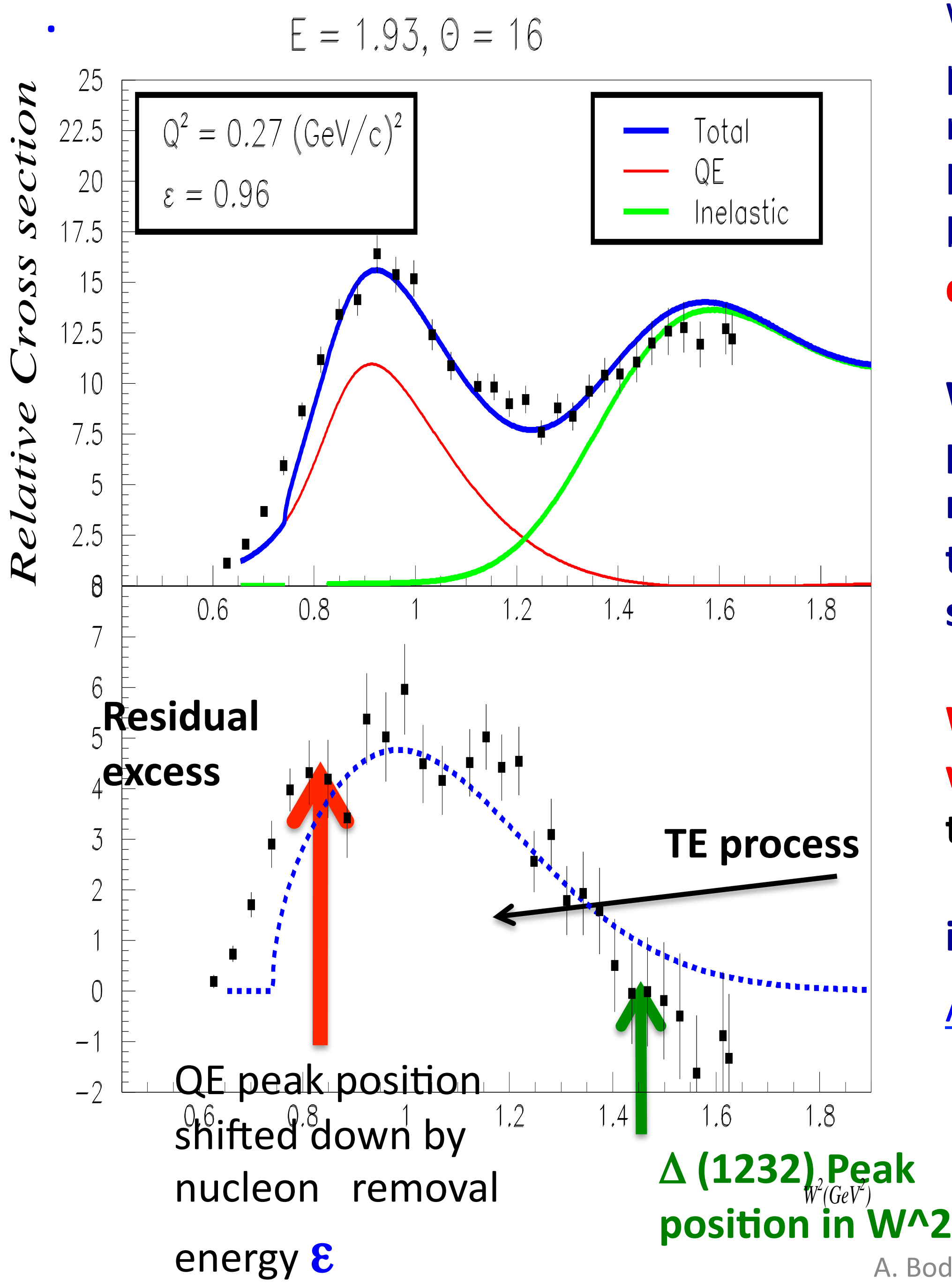
R_T is the ratio of the integrated transverse response function to the integrated longitudinal response function. (Carlson et al integrate the two response functions)



What about higher Q^2

- At low Q^2, the longitudinal response is taken as the response function for independent nucleons. For electron scattering, at low Q^2 the longitudinal contribution dominates and can be taken as the reference. Therefore we use the Carlson *[J. Carson et a. Phys. Rev. C 65 024002 (2002)]* results for RT for **Q^2=0.09 GeV^2 ,Q^2=0.14 GeV^2 and ,Q^2= 0.33 GeV^2**

- At high Q^2, the longitudinal contribution is small, and therefore cannot be a taken as the reference. Instead, we use the predicted QE cross section for the independent nucleon model as the reference.



We compare electron scattering data to the prediction of the sum of an independent QE nucleon model (Psi scaling which is the best known model) plus a Δ resonance smeared by the Fermi gas. → **the sum does not describe the data. There is an excess**

We subtract the sum of QE+ smeared Δ prediction from the data. We integrate the residual excess and divide by the integral of the transverse contribution to the QE cross section and obtain RT (Q2)

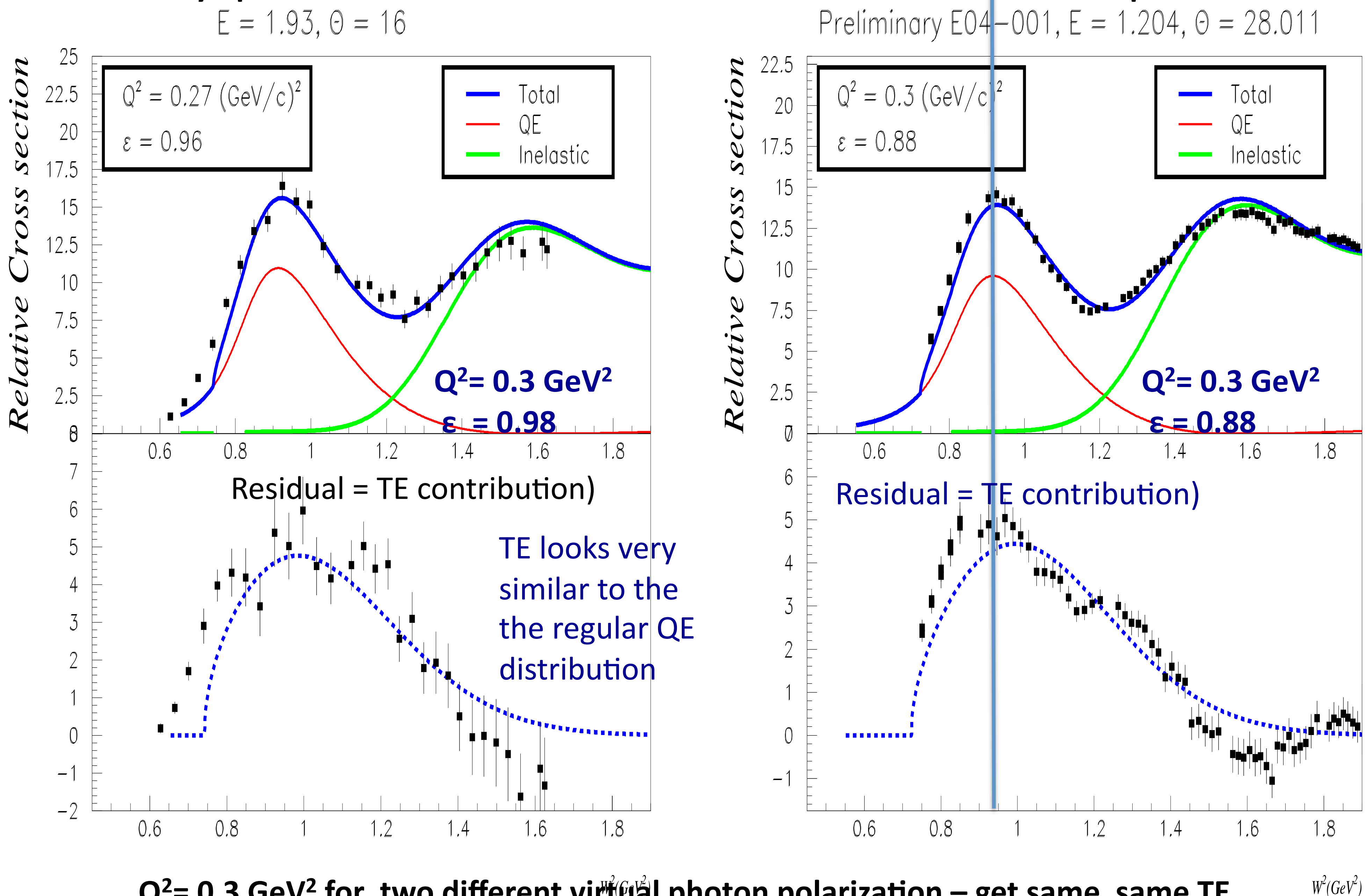
We also extract the peak position and width of the residual excess for the first time.

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

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

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

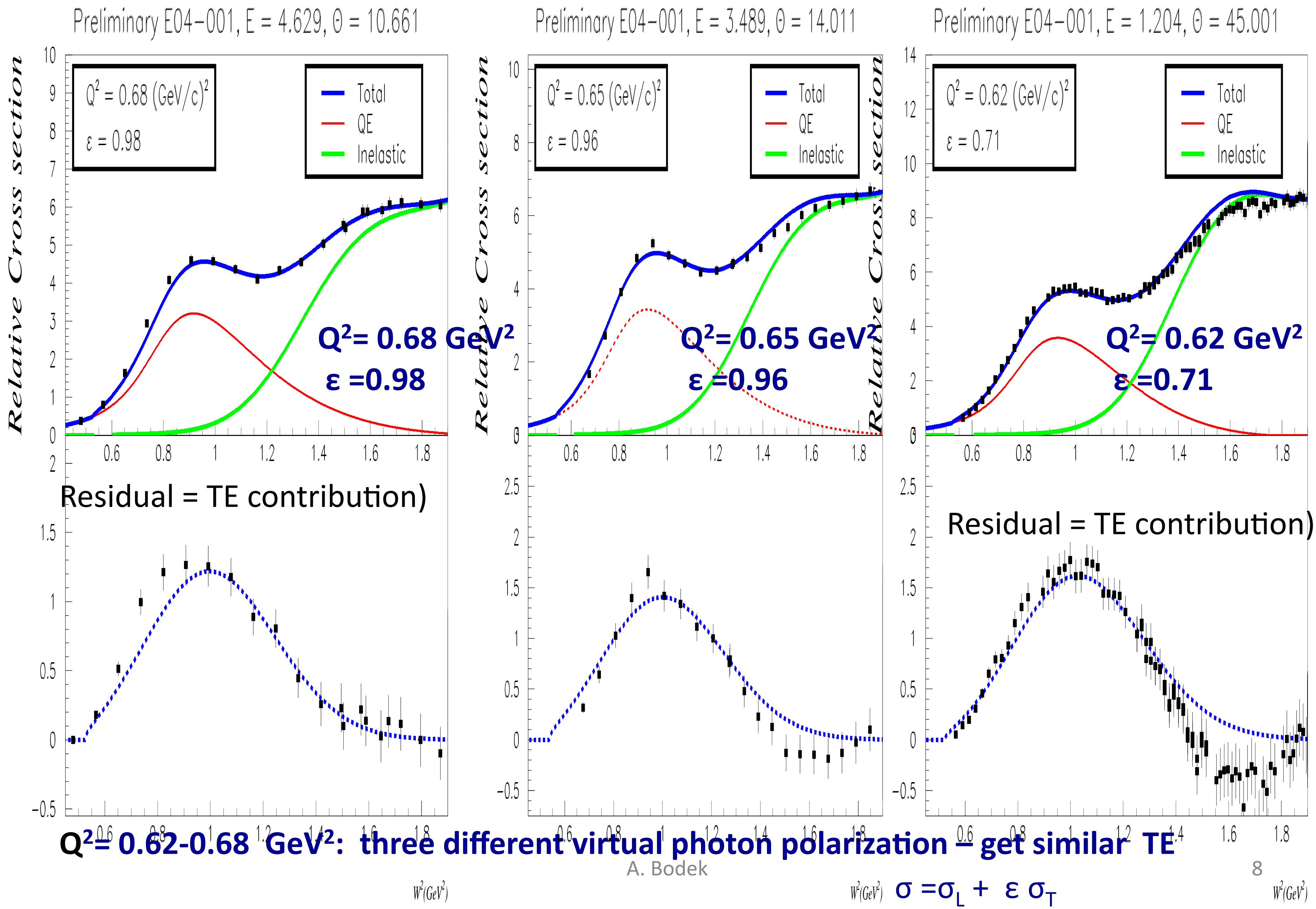
In this study updated the fits to better describe the data. We show a few examples: -



Q^2= 0.3 GeV^2 for two different virtual photon polarization – get same same TE

$\sigma = \sigma_L + \varepsilon \sigma_T$

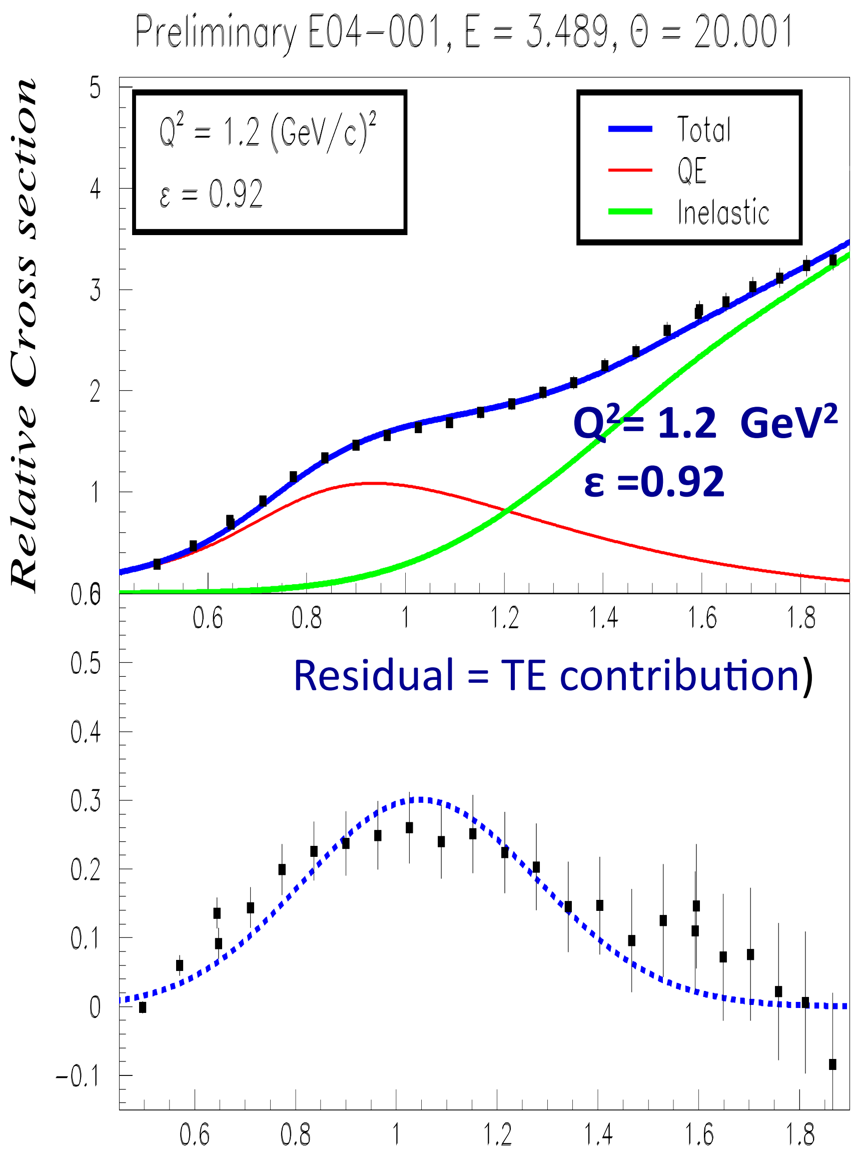
$\sigma = \sigma_L + \varepsilon\, \sigma_T$

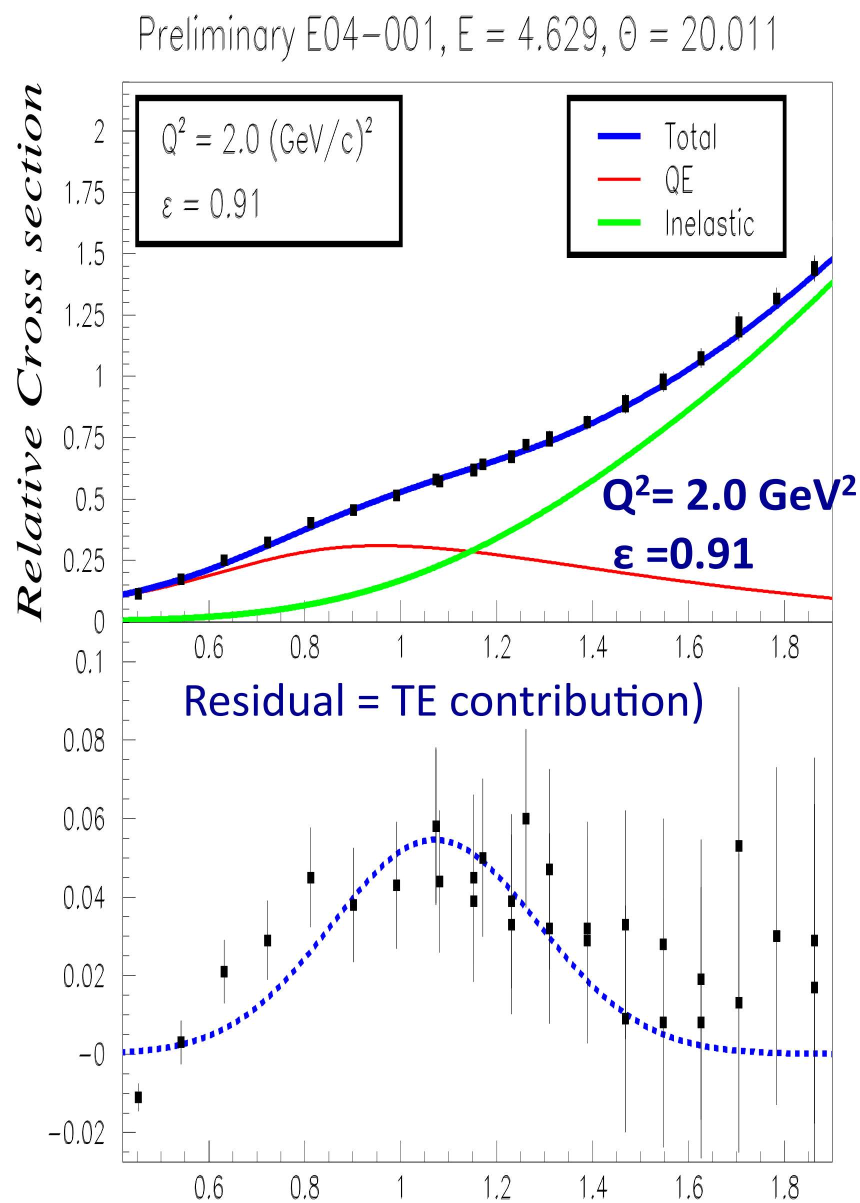


Q^2= 0.62-0.68 GeV^2: three different virtual photon polarization – get similar TE

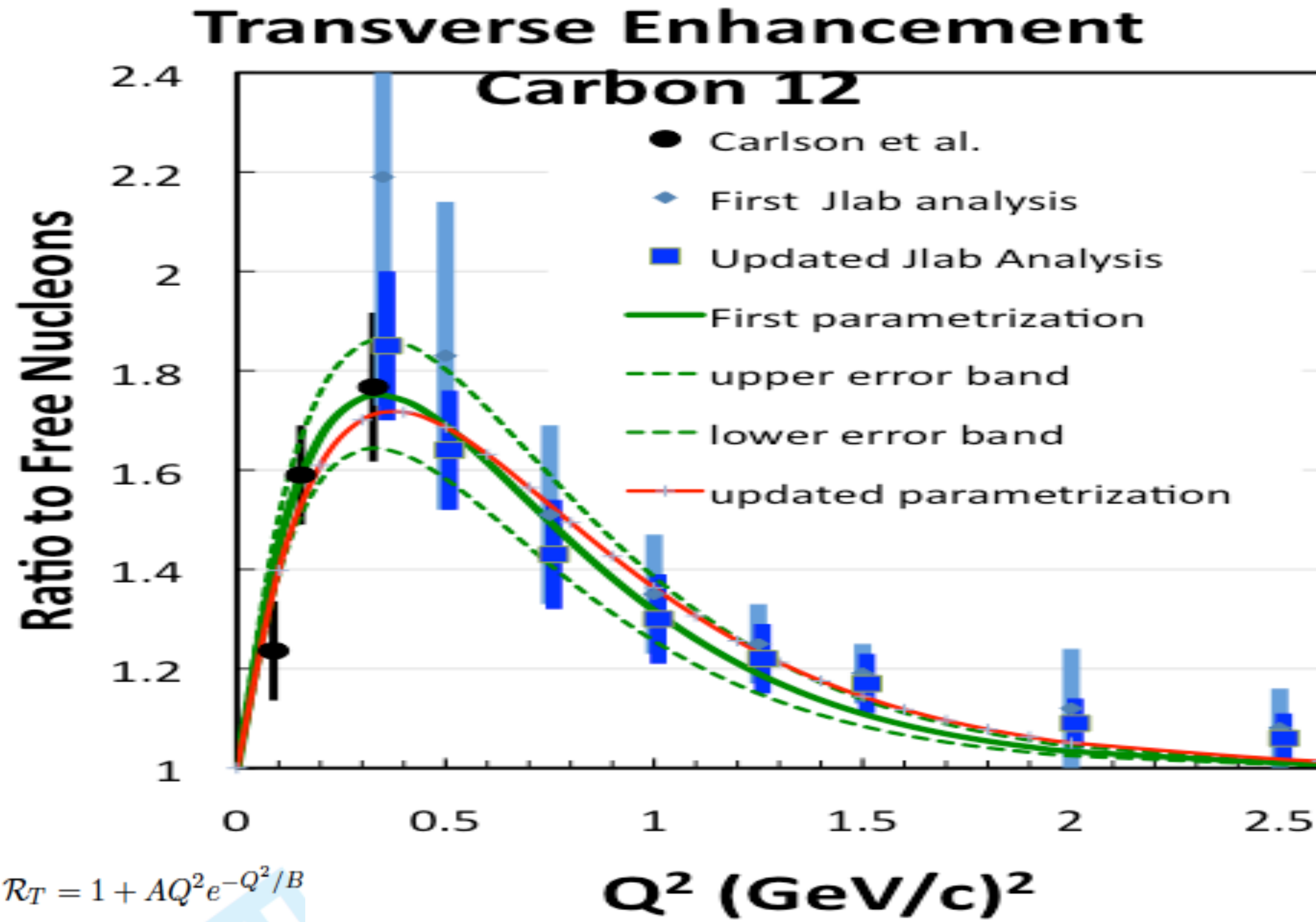
$\sigma = \sigma_L + \varepsilon\, \sigma_T$

$\sigma = \sigma_L + \varepsilon\, \sigma_T$





At high Q^2, the TE/MEC contribution is much smaller (and TE peak is smaller than the QE contribution



$$\mathcal{R}_T = 1 + AQ^2 e^{-Q^2/B}$$

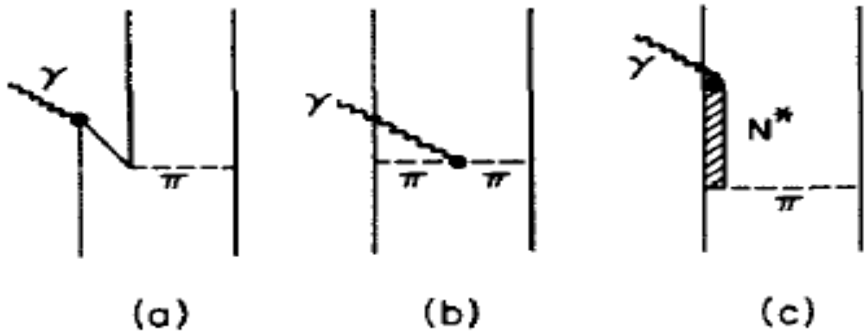
Updated parameterization A= 5.19 and B= 0.376

The original fit(A=6.0 and B=0.34) also describes the new data

Ratio to free nucleons FROM NEW FITS IN BLUE (In these fits, the longitudinal contribution has been assume to have no enhancement).

All three processes interfere.

TE/MEC in the deuteron



MEC process exists for a simple deuteron, it should also exists in a heavy nucleus in which there are many two nucleon pairs which form quasi-deuterons.

process (b) is referred to as the MEC process process (c) is referred to as Isobar excitation.

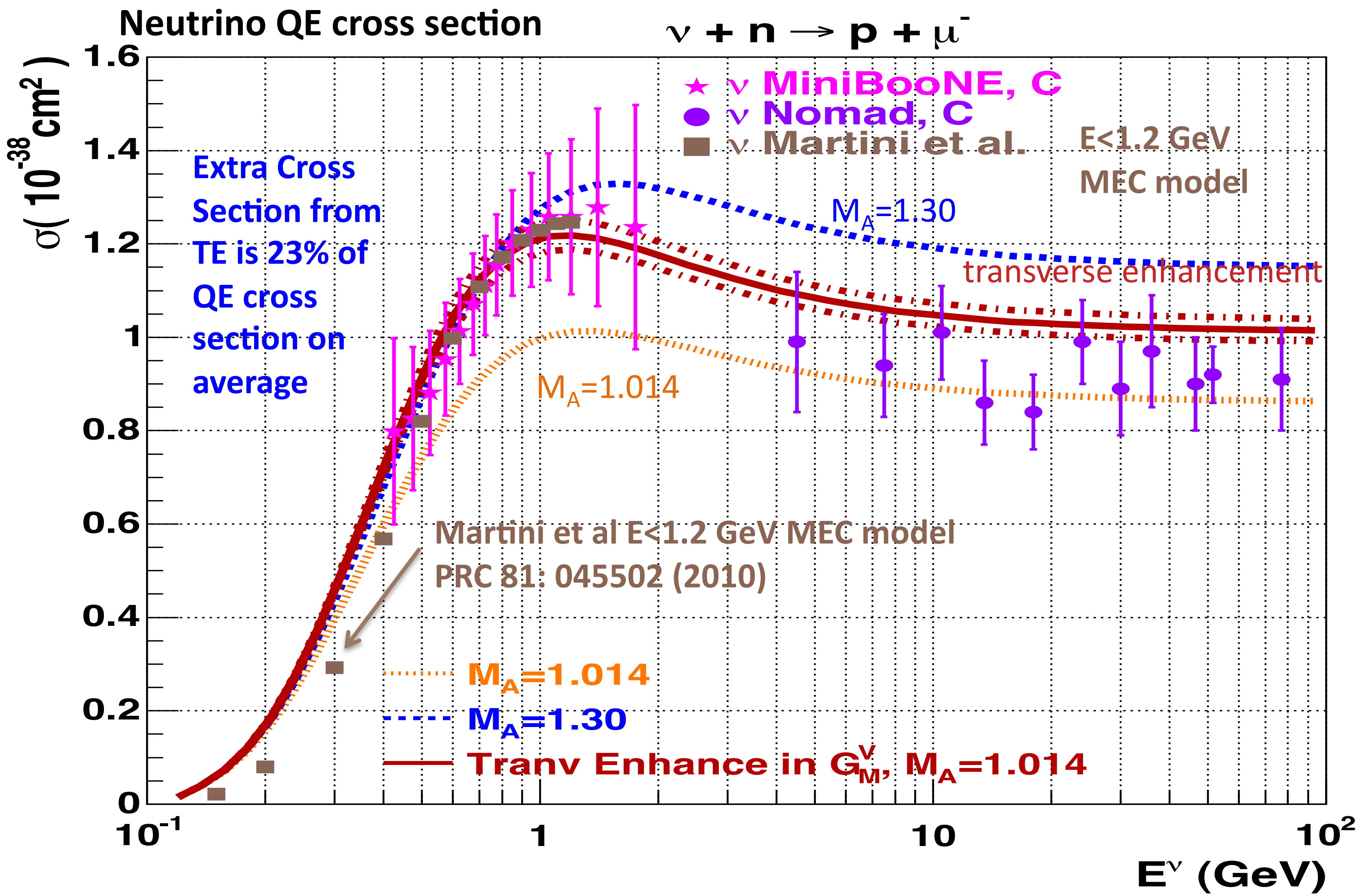
e.g. Δ++ has a magnetic moment about twice that of the proton (2.7) or neutron (-1.9).
So the magnetic form factor of the Δ++ -->Δ++ is 4 times that of of P-->P

If the contribution from virtual isobar excitation (c) to TE is large, then it is reasonable to parameterize TE as larger effective magnetic form factor of the bound nucleon (since the Δ++ is almost purely transverse)

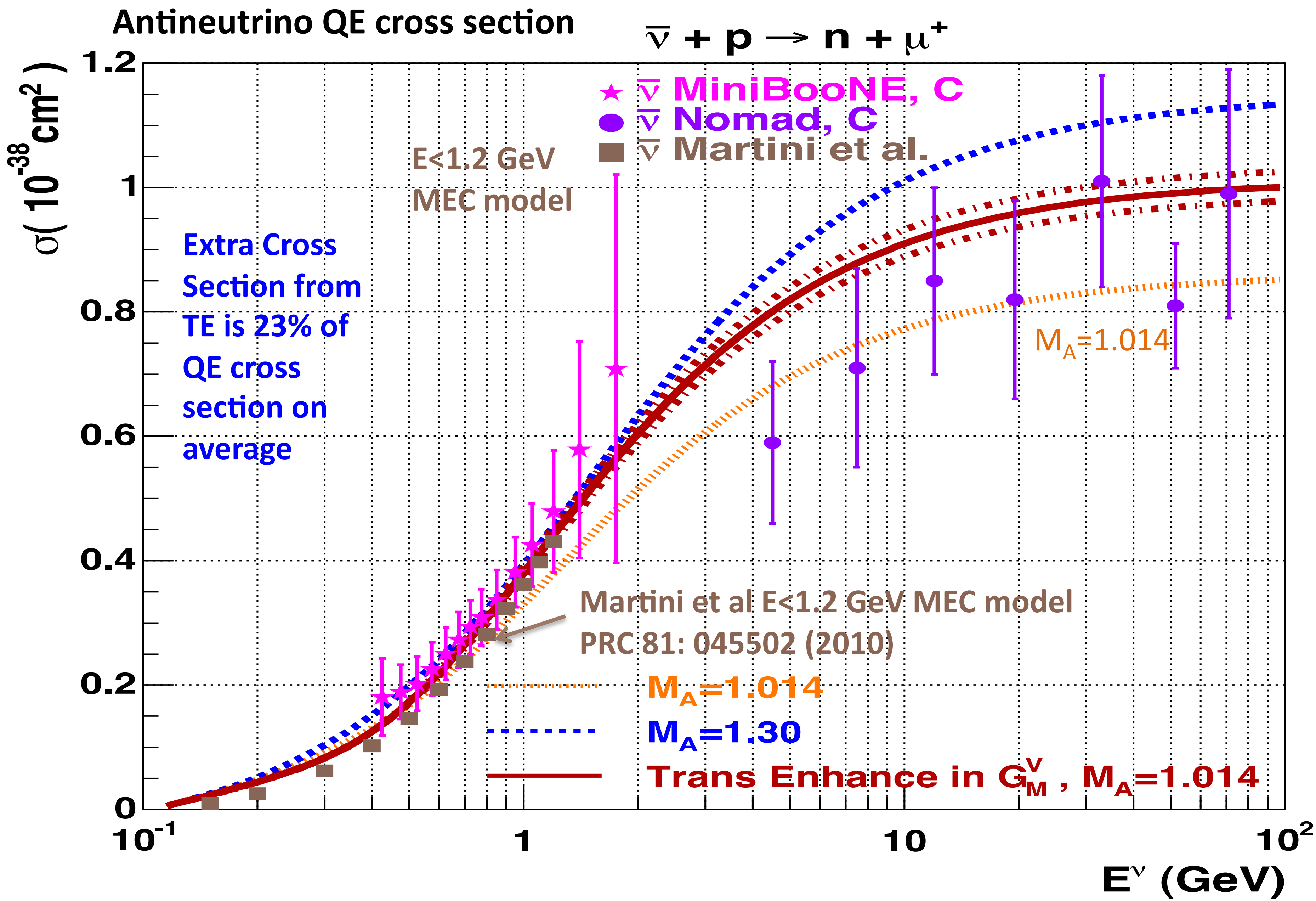
$$G_{Mp}^{nuclear}(Q^2) = G_{Mp}(Q^2) \times \sqrt{1 + AQ^2 e^{-Q^2/B}}$$
$$G_{Mn}^{nuclear}(Q^2) = G_{Mn}(Q^2) \times \sqrt{1 + AQ^2 e^{-Q^2/B}}.$$

(*Note: Unlike electron scattering which is dominated by longitudinal response function at low* $\boldsymbol{Q^2}$*, neutrino cross section is dominated by the transverse part even at low* $\boldsymbol{Q^2}$*)*

We now investigated what this parameterization predicts for neutrino scattering. This model has no free parameters.



Neutrino QE cross section
ν + n → p + μ⁻
σ(10⁻³⁸cm²)
ν MiniBooNE, C
ν Nomad, C
ν Martini et al.
E<1.2 GeV
MEC model
Extra Cross
Section from
TE is 23% of
QE cross
section on
average
M_A=1.30
transverse enhancement
M_A=1.014
Martini et al E<1.2 GeV MEC model
PRC 81: 045502 (2010)
M_A=1.014
M_A=1.30
Tranv Enhance in G_M^V, M_A=1.014
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
10⁻¹
1
10
10²
E^ν (GeV)

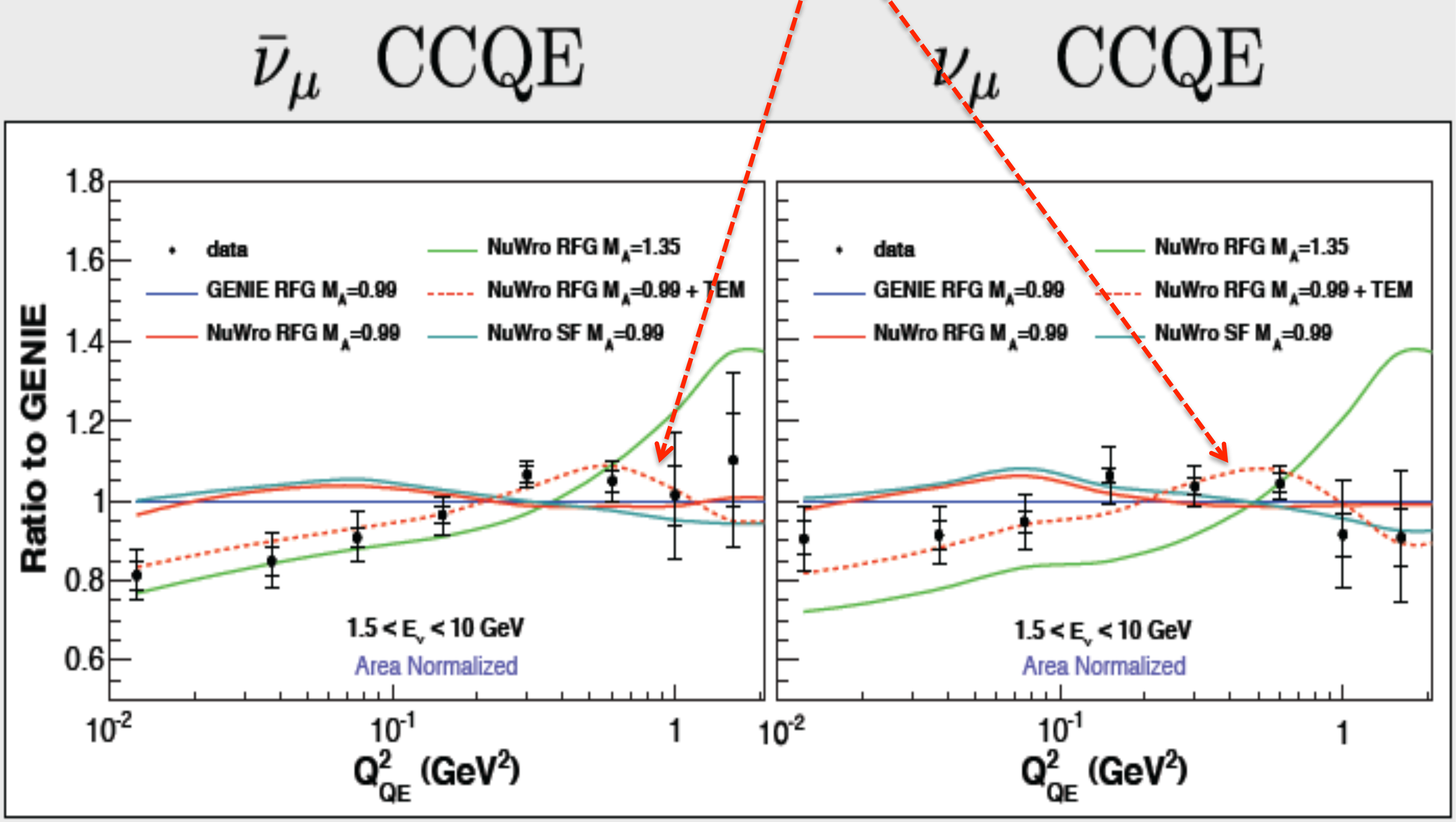


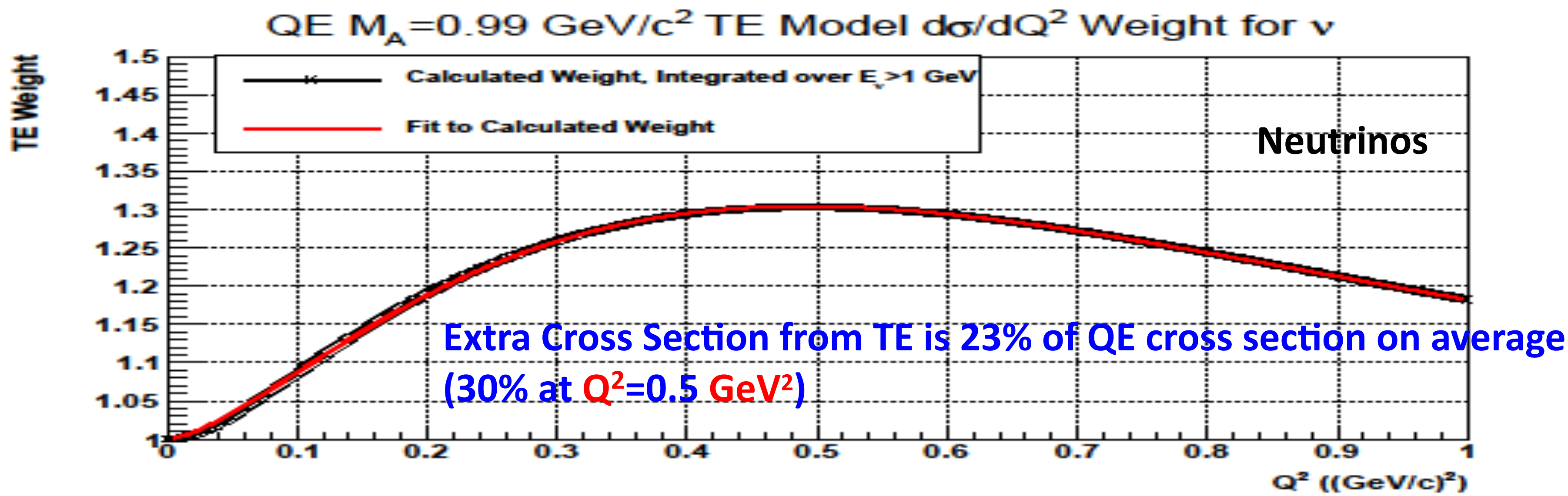
Antineutrino QE cross section
ν̄ + p → n + μ⁺
σ(10⁻³⁸cm²)
1.2
1
0.8
0.6
0.4
0.2
0
10⁻¹
1
10
10²
Eᵛ (GeV)
ν̄ MiniBooNE, C
ν̄ Nomad, C
ν̄ Martini et al.
E<1.2 GeV
MEC model
Extra Cross
Section from
TE is 23% of
QE cross
section on
average
M_A=1.014
Martini et al E<1.2 GeV MEC model
PRC 81: 045502 (2010)
M_A=1.014
M_A=1.30
Trans Enhance in G_M^V , M_A=1.014

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

$d\sigma/dQ^2$ Shape

TE model dashed red line - - - - - - - - -





Ratio of neutrino QE $d\sigma_{QE}/dQ^2$ with and without TE.

For neutrino energies greater than 1 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 functional form to weight GENIE QE events to include TE (this requires no change in GENIE).

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

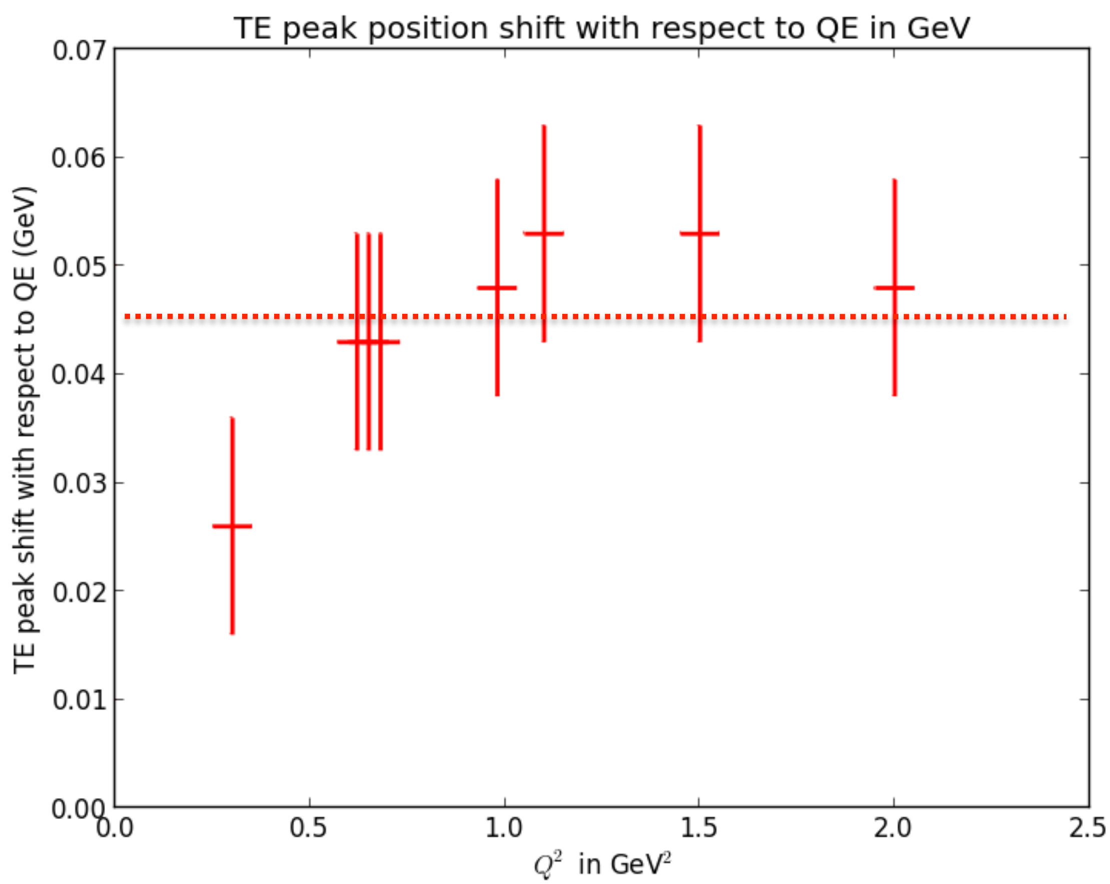
This weighting include the effect of TE on average, it accounts for the increase in the total cross section, and for the change in shape of the Q^2 distribution. However, it will not account for possible difference in shape in ν (hadron energy) for QE and TE

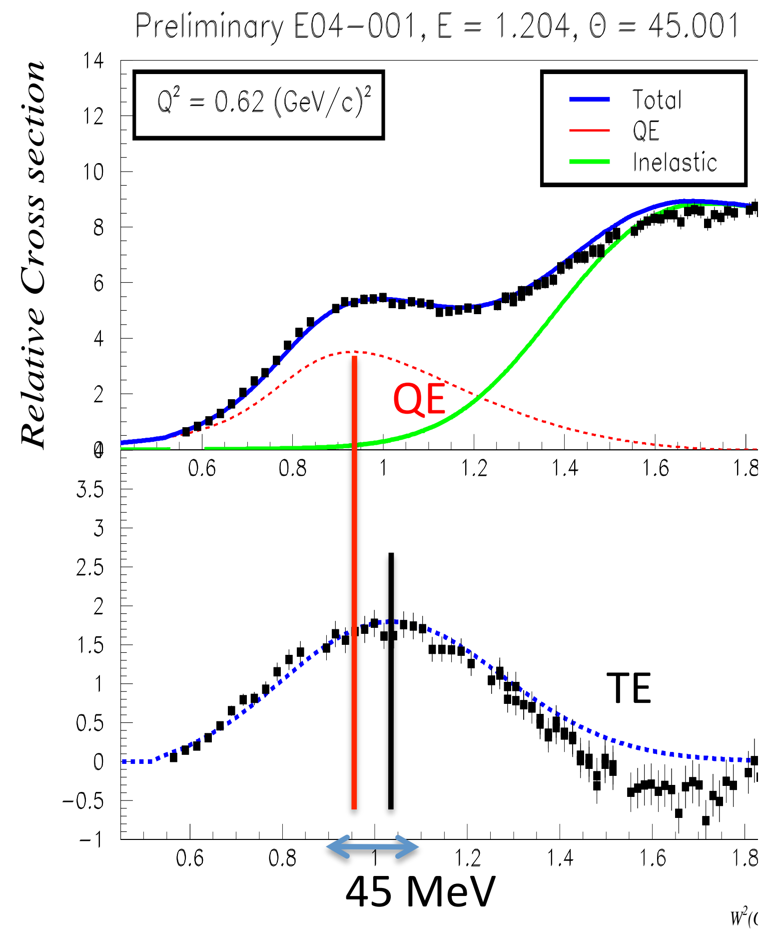
Investigation of peak and width of TE

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

- Therefore, we now compare the shape of the QE and TE components.

Comparison of peak position of TE and QE





- Difference is 45 MeV.
- TE peak is about 45 MeV higher in ν than the independent nucleon QE peak.

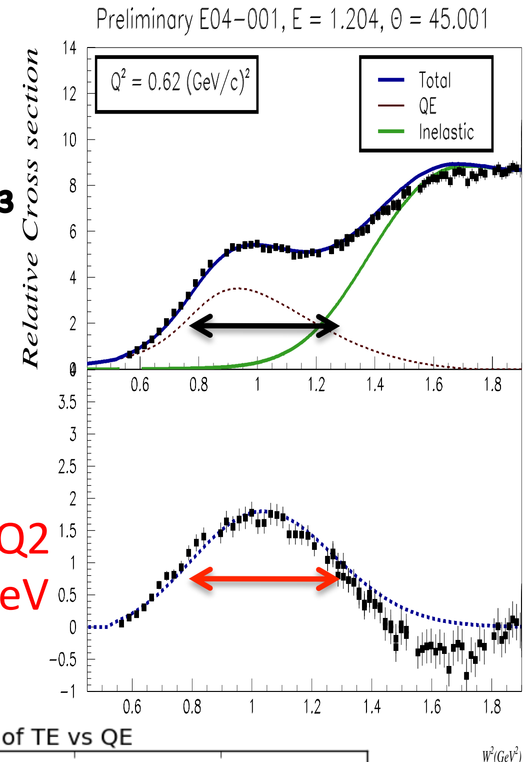
RMS width of the ν distribution
For QE scattering with Fermi momentum k

Simple derivation:
QE scattering with Fermi motion k. $W^2=M^2$
$W^2=M^2 + 2M\nu - 2k*q - Q^2$ --→ $\nu = Q^2/2M + k*q/M$

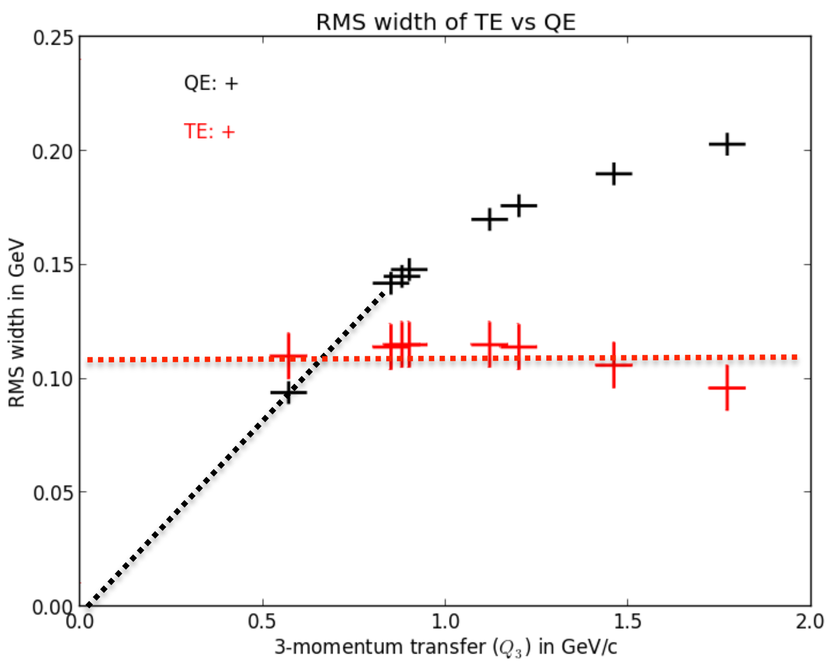
$<\nu>_{RMS} = <k*q_3/M> = Q_3<k_3>/M$
With $Q_3 = \mathrm{sqrt}\ \{Q^2 (1+ Q^2/4M^2)\}$
expect RMS increases with q3 with a slope of K_3/M

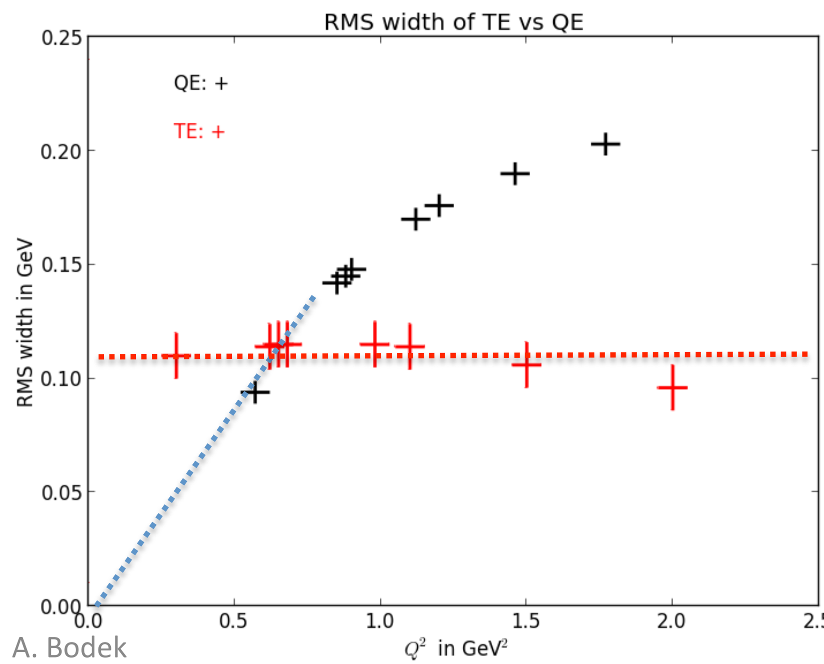
Here k_3 is the Fermi momentum along Q_3 which is the 3-momentum transfer to the nucleon.

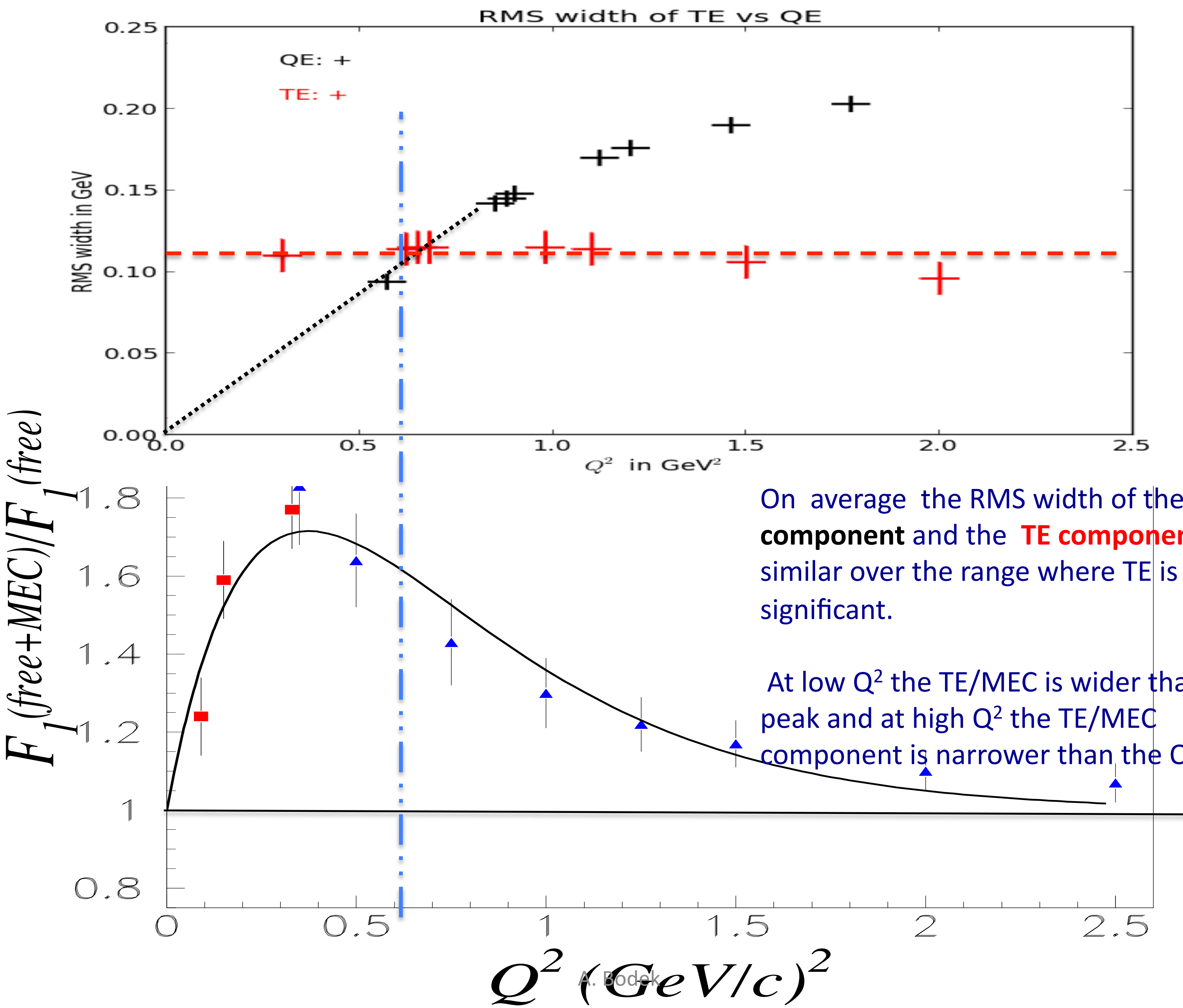
RMS width of QE rising with Q_3
RMS ~ 0.15 GeV x Q_3



RMS width TE independent of Q2
$<\nu>_{RMS} = 0.11$ GeV







On average the RMS width of the **QE component** and the **TE components** are similar over the range where TE is significant.

At low Q^2 the TE/MEC is wider than the QE peak and at high Q^2 the TE/MEC component is narrower than the QE peak.

Conclusions on TE

- We have updated the analysis of the Q^2 dependence of TE. The updated analysis has smaller error bars and yields somewhat lower TE contribution vs Q^2. Although we have a new parameterization, the original parameterization still describes the new data reasonably well.

$$\mathcal{R}_T = 1 + AQ^2 e^{-Q^2/B}$$

Updated parameterization A= 5.19 and B= 0.376

- TE increases the QE cross section and changes the shape of $d\sigma_{QE}$. This can be included in Neutrino MC generators by a simple Q^2 dependent weight. The Q^2 dependent weight is the same for neutrinos and antineutrinos.

We also extracted the peak position and shape (width) in ν for the TE as a function of Q^2.

- The TE peaks relative to the QE peak positions are shifted by 45 MeV towards higher ν. The shifts are independent of Q^2.
- The RMS widths of the ν distribution of TE are about 110 MeV and are also independent of Q^2.

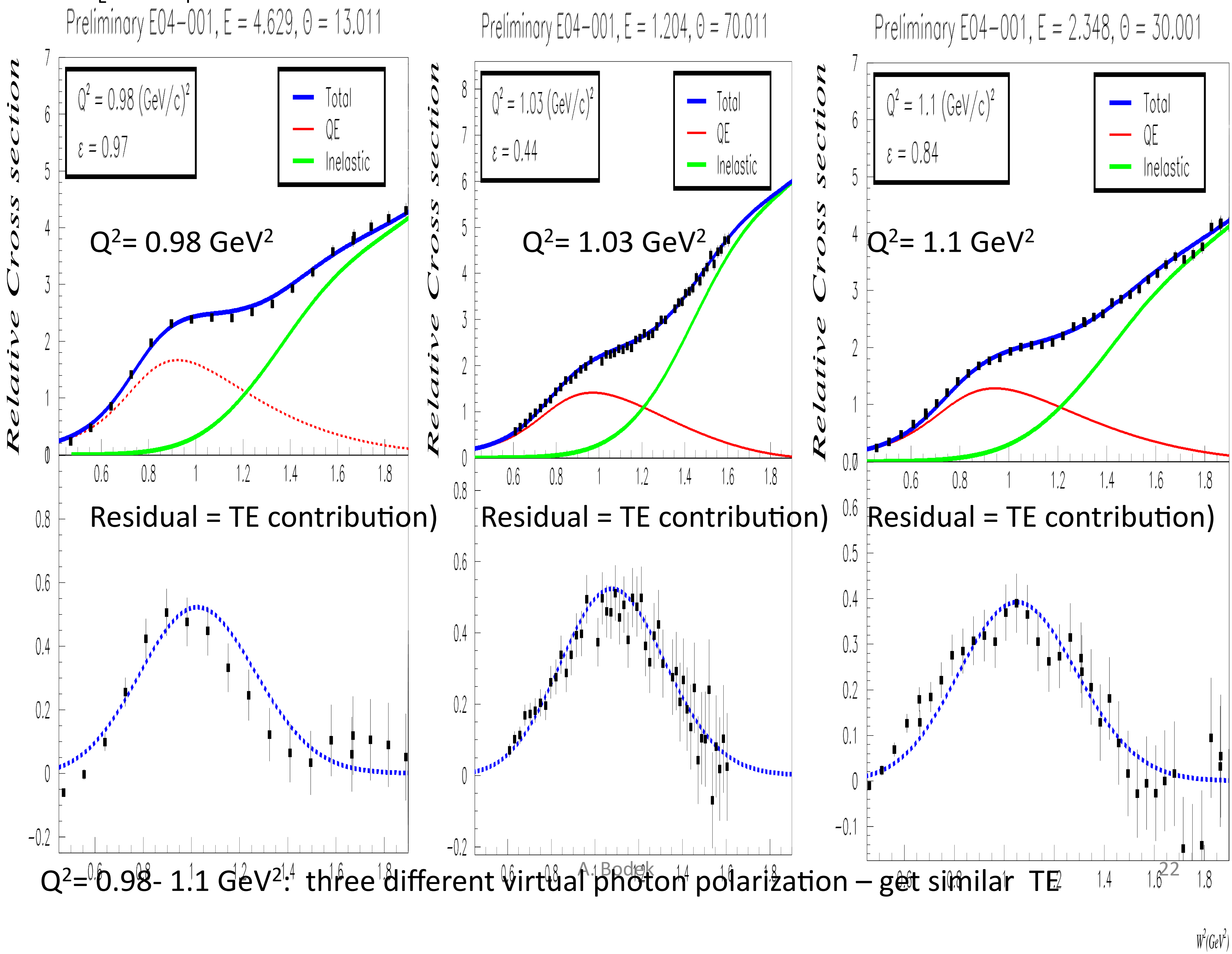
If we average over the Q^2 range where TE is significant, the TE and QE distributions are similar.

This is the reason why the simple assumption that TE can be described as increasing the effective magnetic form factors of bound nucleons works reasonably well. However, some deviations from the predictions of the enhanced magnetic form factor model are expected

- We are currently extending the analysis lower Q^2 (< 0.3 GeV2) to overlap with our analysis of the low Q^2 L-T separated results from Carlson et al.
- NOTE: These precise electron scattering data provide a benchmark against which microphysical MEC models (such as 2p2h) can be tested.

Extra slides

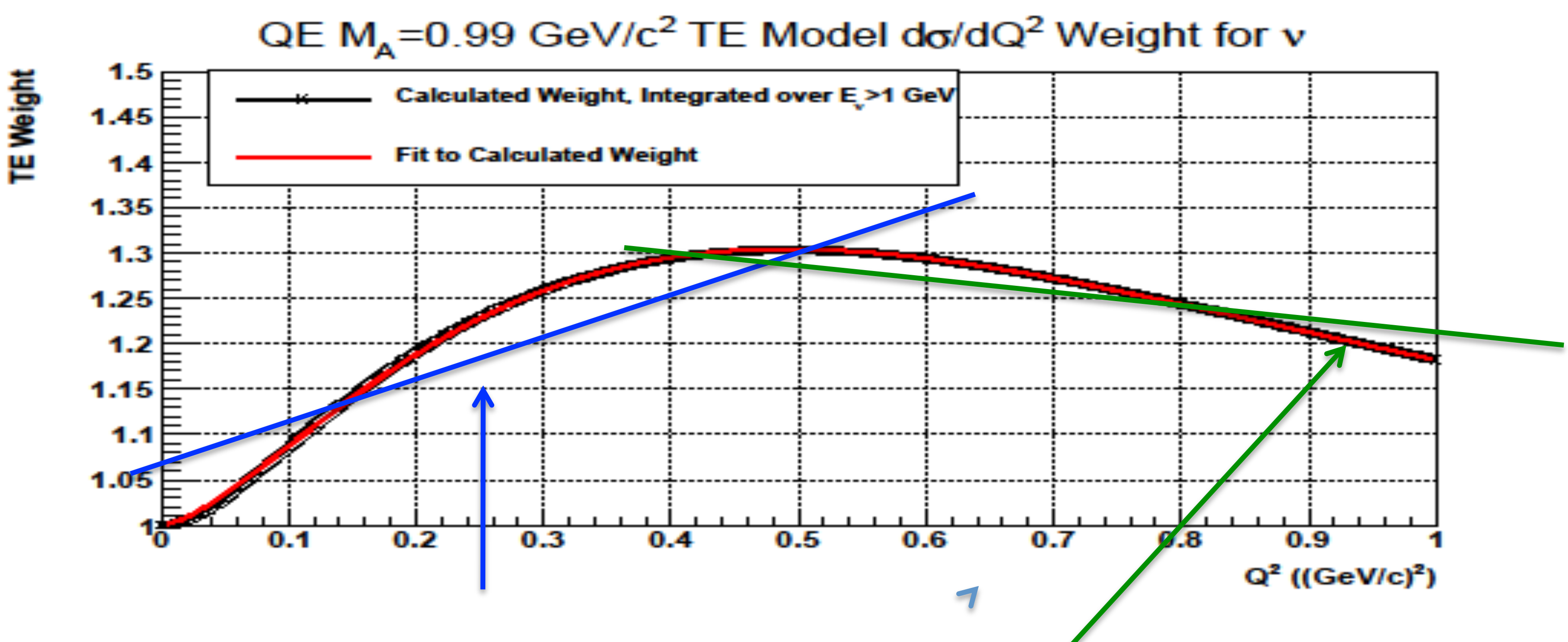
$\sigma = \sigma_L + \varepsilon\, \sigma_T$



Q^2= 0.98- 1.1 GeV^2: three different virtual photon polarization – get similar TE

Why MiniBooNE finds a large MA while Higher energy experiments find a smaller MA.

If you include TE, all experiments should get MA=1. What if TE is not included?

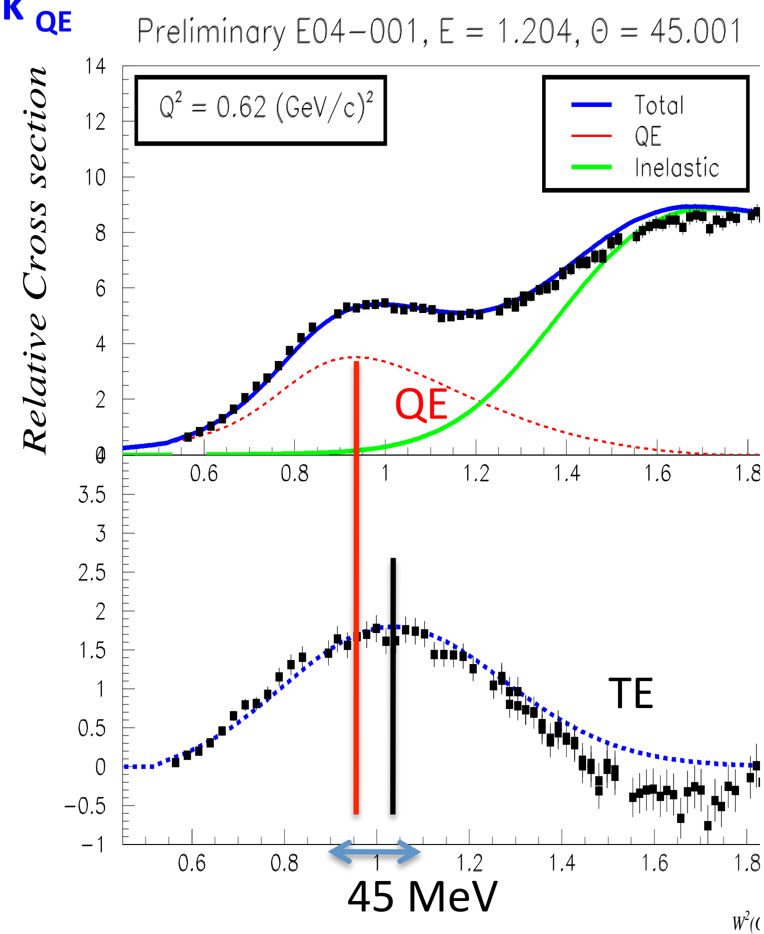


MiniBoone has a low Q2 max, can only fit low Q2. Get MA>1 since the don't include TE

High energy experiments remove low Q2 data from fit. Get MA<1 since they don't include TE

Comparison of peak position of TE and QE

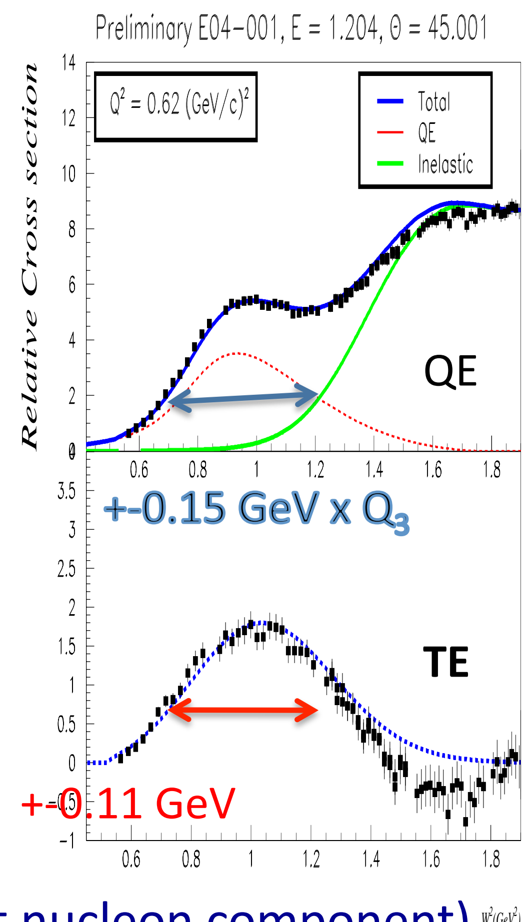
Q^2 GeV^2	Peak ν_{QE} GeV	Peak ν_{TE} GeV	Peak$_{TE}$ - Peak$_{QE}$ GeV
0.3	0.175	0.201	0.026
0.62	0.345	0.388	0.043
0.65	0.361	0.404	0.043
0.68	0.377	0.42	0.043
0.98	0.537	0.585	0.048
1.1	0.601	0.654	0.053
1.5	0.814	0.867	0.053
2	1.08	1.128	0.048
		Average	0.045



- Difference is 45 MeV.
- TE peak is about 45 MeV higher in ν than the independent nucleon QE peak.

Comparison of RMS *width* position of TE versus QE

Q^2 GeV^2	q3 GeV	RMS width of ν_{QE} GeV	RMS with of ν_{TE} GeV
0.3	0.57	0.094	0.11
0.62	0.85	0.142	0.114
0.65	0.88	0.145	0.115
0.68	0.90	0.148	0.115
0.98	1.12	0.17	0.115
1.1	1.20	0.176	0.114
1.5	1.46	0.19	0.106
2	1.77	0.203	0.096
		Avearge	0.111



•The RMS width of the ν distribution of QE (independent nucleon component) increases with Q^2 as expected from Fermi motion (shown on the next slide) **RMS_QE= 0.15 GeV x Q_3)**

•In contrast, the RMS width of the ν distribution of TE component is 0.11 GeV on average and independent of Q^2.