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

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Neutrino Session, Thursday Aug. 15, 2013

9:30 – 10:00 AM (abstract 263)

Jupiter Collaboration (Jlab E04-001)

A. Bodek, Cynthia Keppel, Eric Christy Spokespersons

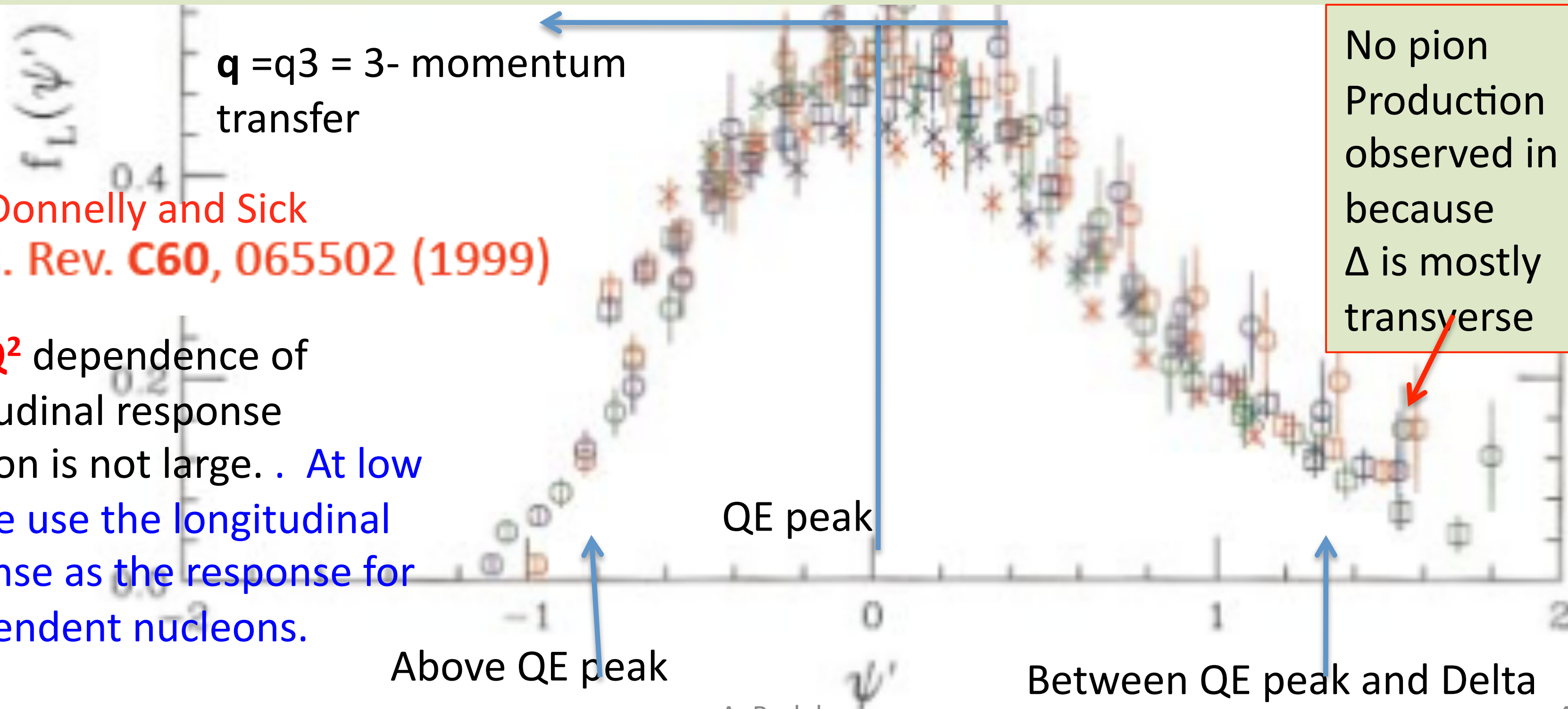
- Measured electron scattering cross sections on nucleon and nuclear targets in the few GeV region.
- Use these new measurements in conjunction with all previous electron scattering data to extract the vector contributions (form factors, structure functions, QE nuclear response functions, etc.) to neutrino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

Electron QE scattering: Longitudinal Response Function

There are many measurements of differential QE cross section in electron scattering. If we assume free nucleon form factors, and remove their Q2 dependent contribution, **what is left is defined as the nuclear response function** (which is plotted vs the scaling variable Psi)
What is found is that the response function is universal for A>12. It does not depend on momentum transfer, as expected for scattering from independent nucleons
Therefore, for longitudinal QE scattering the data is in agreement with the INDEPENDENT NUCLEON MODEL WITH FREE NUCLEON FORM FACTORS. Deviations from scaling for the Longitudinal response function are not big.



q =q3 = 3- momentum transfer

Donnelly and Sick
Phys. Rev. **C60**, 065502 (1999)

The Q^2 dependence of longitudinal response function is not large. . At low Q2, we use the longitudinal response as the response for independent nucleons.

QE peak

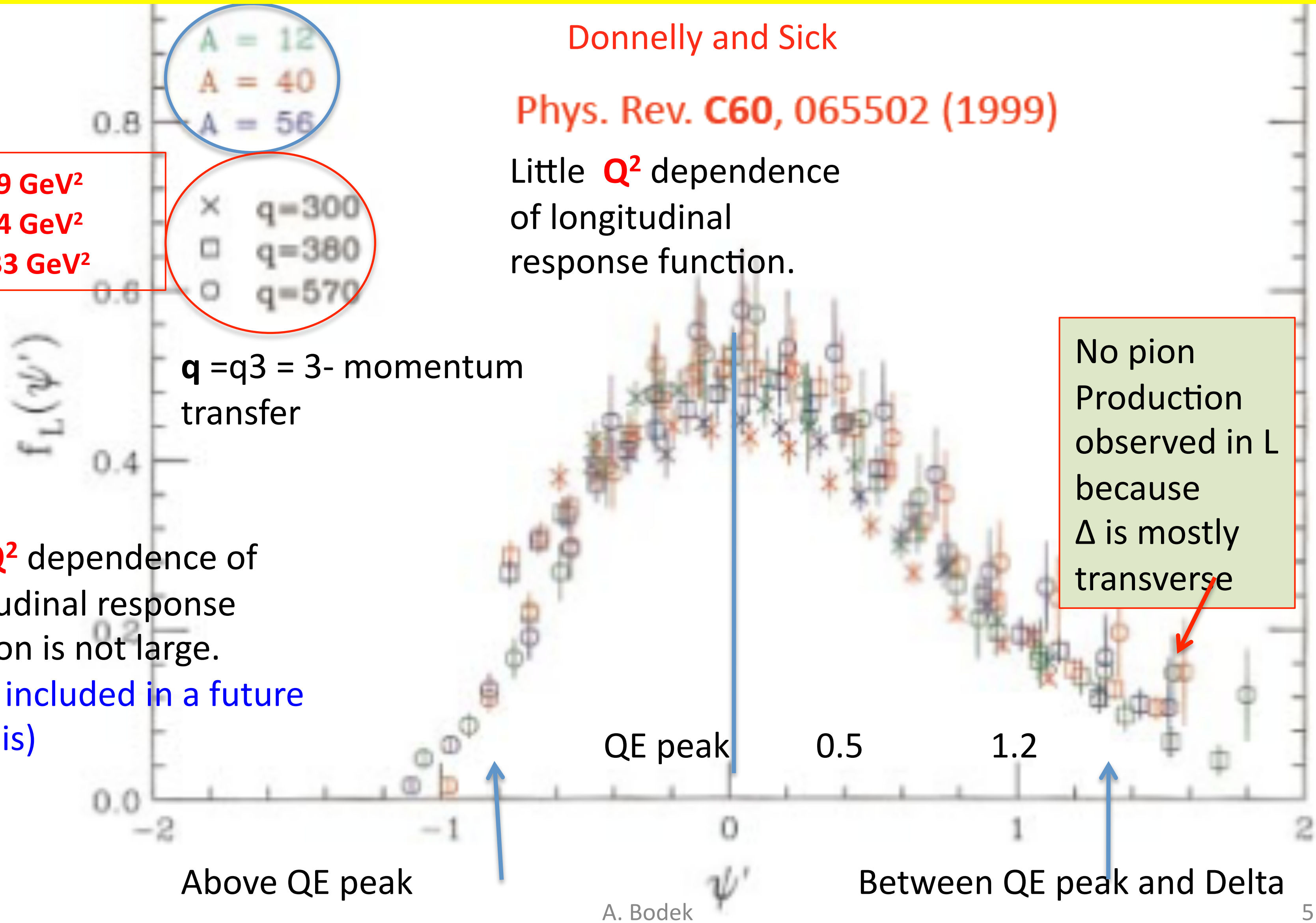
Above QE peak

Between QE peak and Delta

No pion Production observed in L because Δ is mostly transverse

Electron QE scattering: Longitudinal Response Function for Q^2=0.09 GeV^2 Q^2=0.14 GeV^2 Q^2= 0.33 GeV^2

Use this as the shape of the universal response function



Donnelly and Sick

Phys. Rev. **C60**, 065502 (1999)

Q^2=0.09 GeV^2
Q^2=0.14 GeV^2
Q^2= 0.33 GeV^2

Little Q^2 dependence of longitudinal response function.

q =q3 = 3- momentum transfer

No pion Production observed in L because Δ is mostly transverse

The Q^2 dependence of longitudinal response function is not large.
(to be included in a future analysis)

QE peak 0.5 1.2

Above QE peak

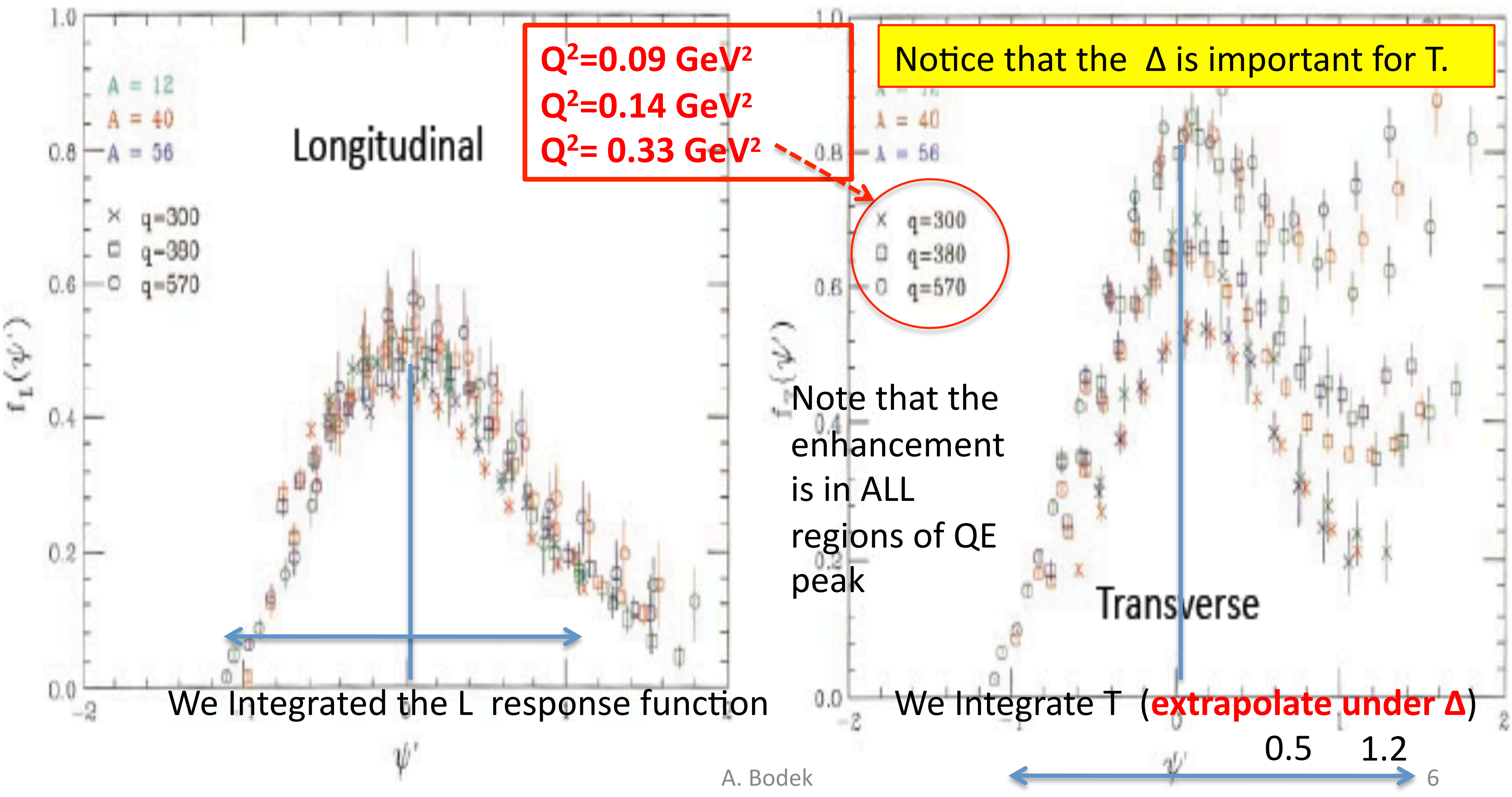
Between QE peak and Delta

Donnelly and Sick Phys. Rev. **C60**, 065502 (1999)

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



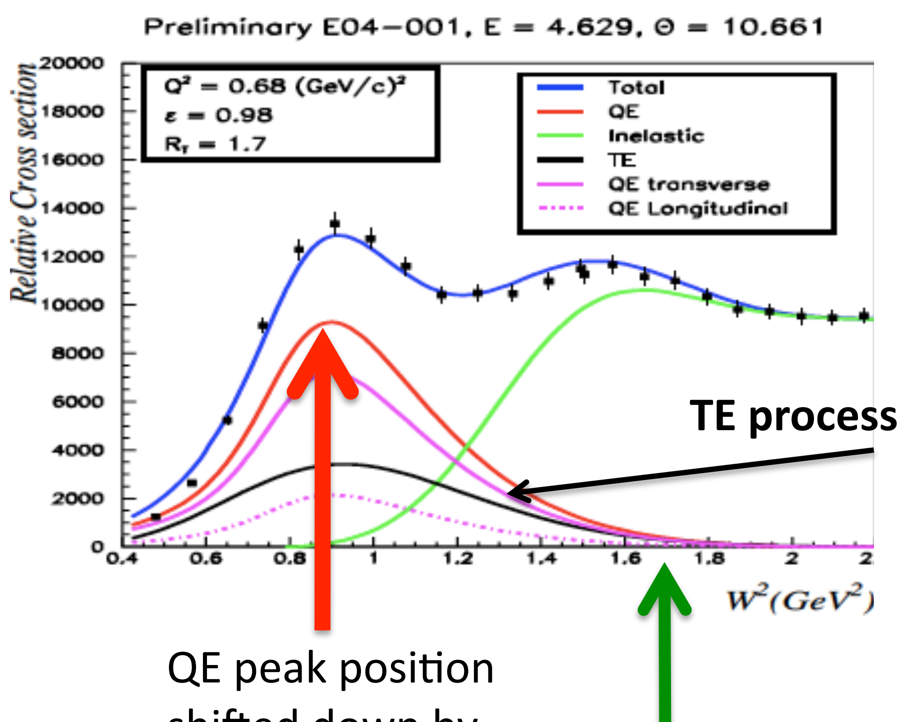
What about higher Q^2

- 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.

- 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.

In our previous studies , we extended the studies of TE to higher Q2 by using existing (Bosted-Mamyan) fits to electron scattering data (which were done for purpose of doing radiative corrections).

When electron scattering data was compared to the prediction of the sum of an independent QE nucleon model (Psi scaling which is the best known model) plus a Delta resonance smeared by the Fermi gas. → It was found that the sum does not describe the data



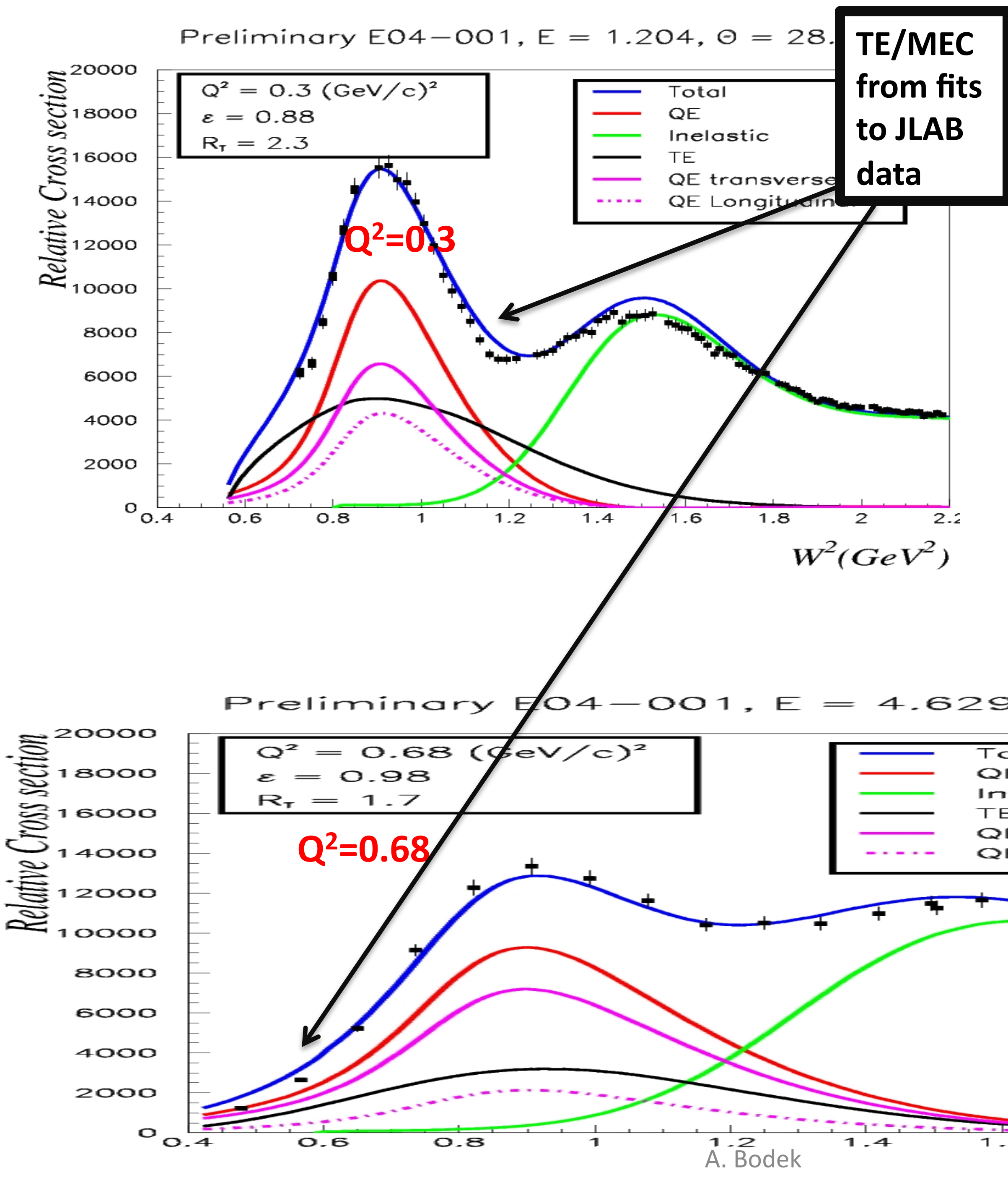
QE peak position shifted down by nucleon removal energy ε

Δ (1232) Peak position in W^2

Therefore, Bosted and Manyan added Transverse Enhancement (TE/MEC) contribution. This TE contribution was parametrized by a distorted Gaussian shown as a black line. (These fits were done for the purpose of radiative corrections.)

In order to predict the magnitude of the TE in neutrino scattering, we integrated the TE/MEC Gaussian from the Bosted-Mamyan fit for different spectra at fixed Q^2 and extracted RT.
(The Gaussian fit to TE/MC was not perfect and this was included this in our systematic error).

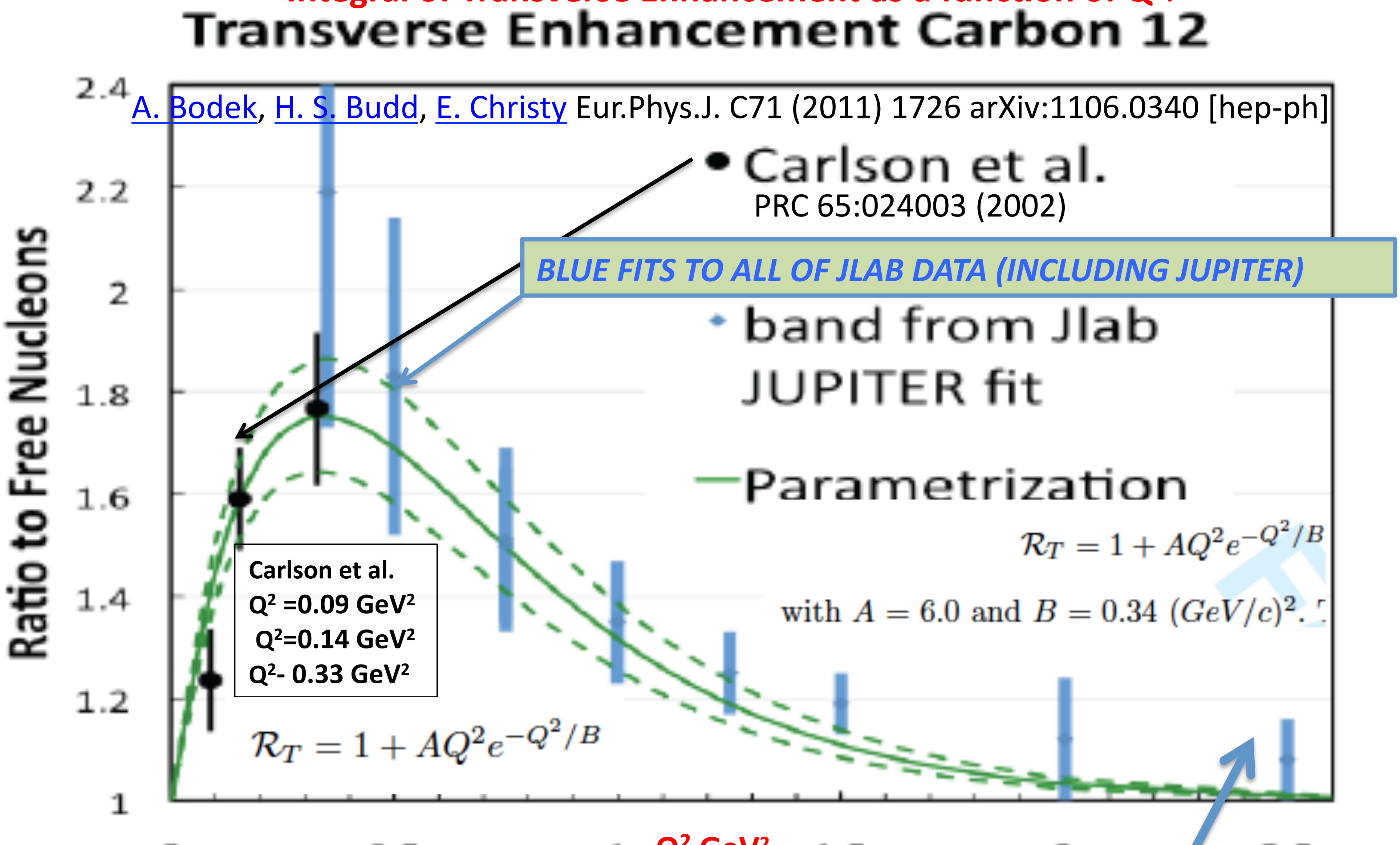
A. Bodek, H. S. Budd, E. Christy
Eur.Phys.J. C71 (2011) 1726 arXiv:1106.0340 [hep-ph]



If you look at the width of the distributions of TE. For the lower Q^2 the Bosted-Mamyan somewhat overestimated the tails of the TE contribution.

We have now repeated these fits with a specific focus on investigating the magnitude, peak position and width of the TE contribution.

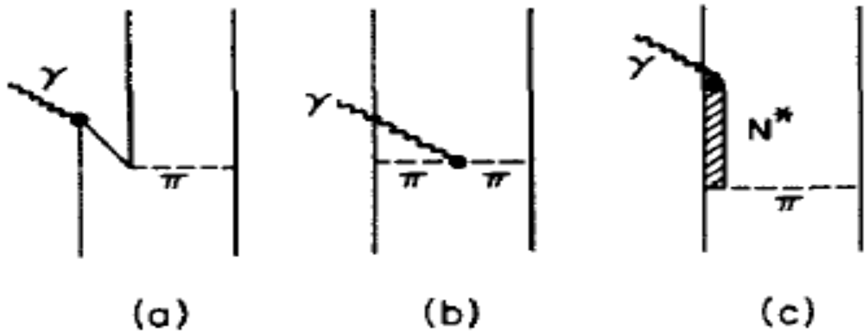
Integral of Transverse Enhancement as a function of Q^2.



We find that the transverse enhancement at high Q^2 is small. This means that neutrino experiments on nuclear targets can be used to measure the axial form factor at high Q2

.

All three processes interfere.



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

Δ++ has a magnetic moment of 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* ***Q^2****, neutrino cross section is dominated by the transverse part even at low* ***Q^2****)*

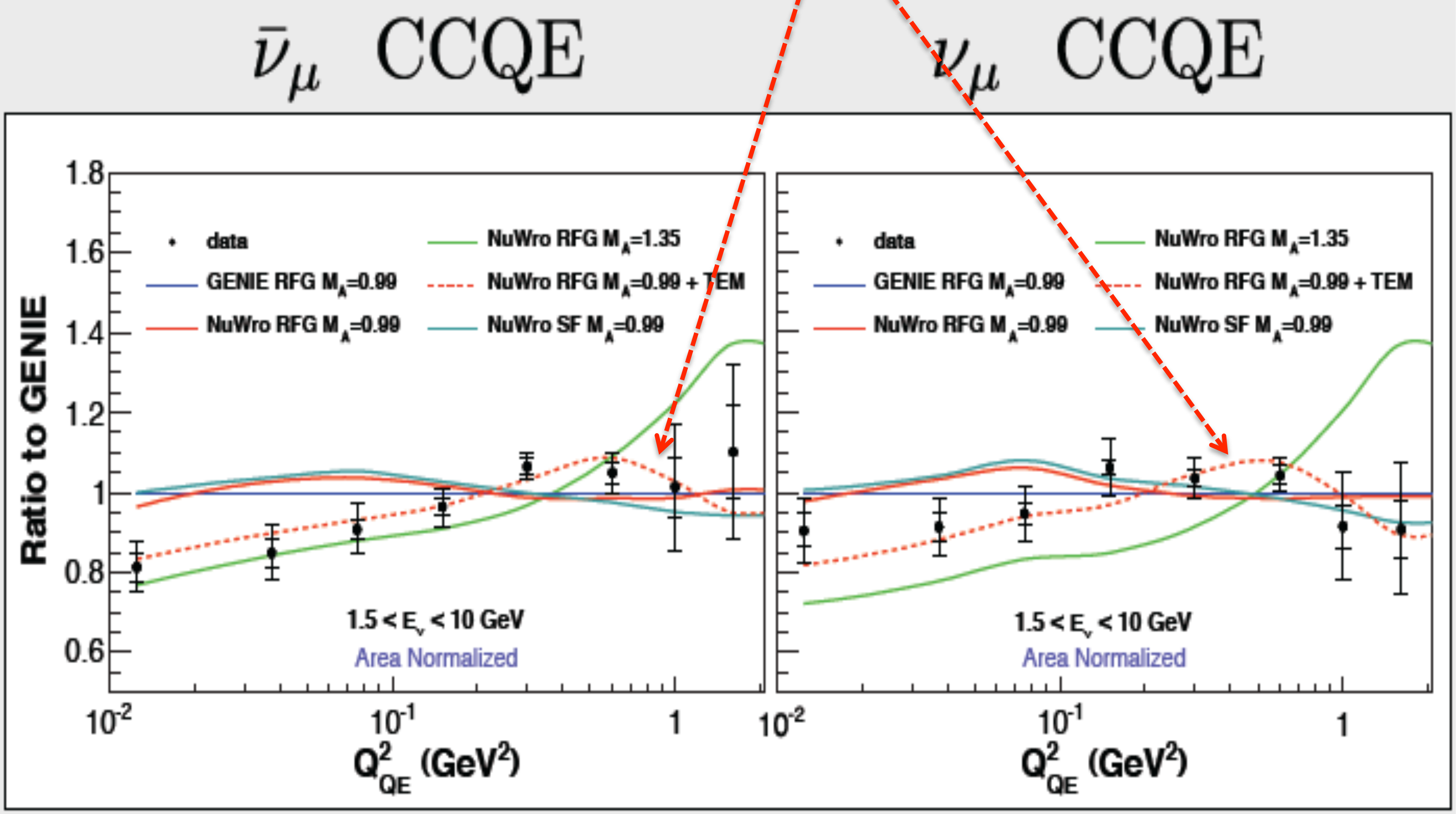
We now investigated what this parameterization predicts for neutrino scattering.

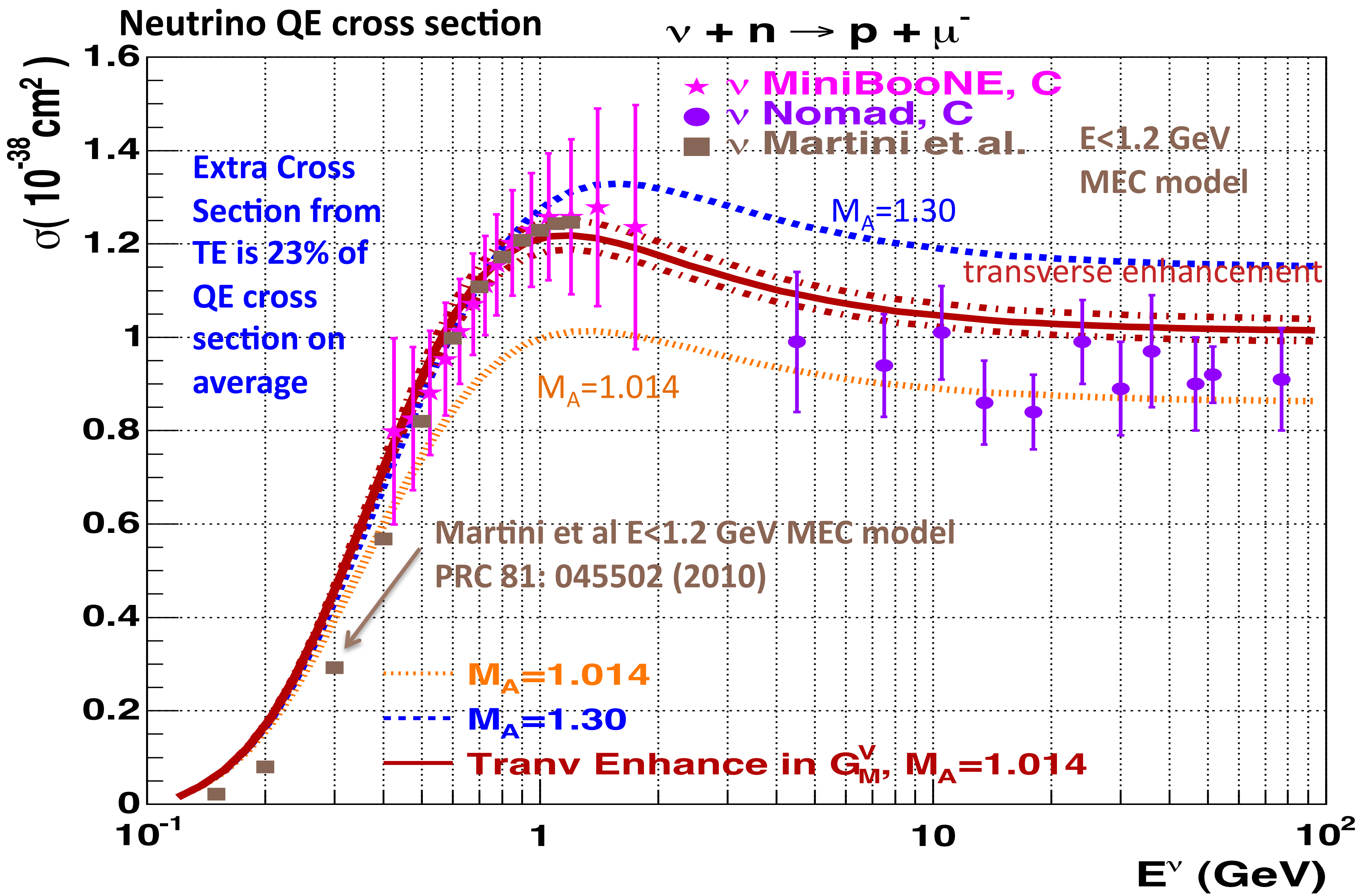
1. Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at *Ev*~3.5 GeV MINERvA Collaboration . May 9, 2013 e-Print: **arXiv:1305.2243**

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**

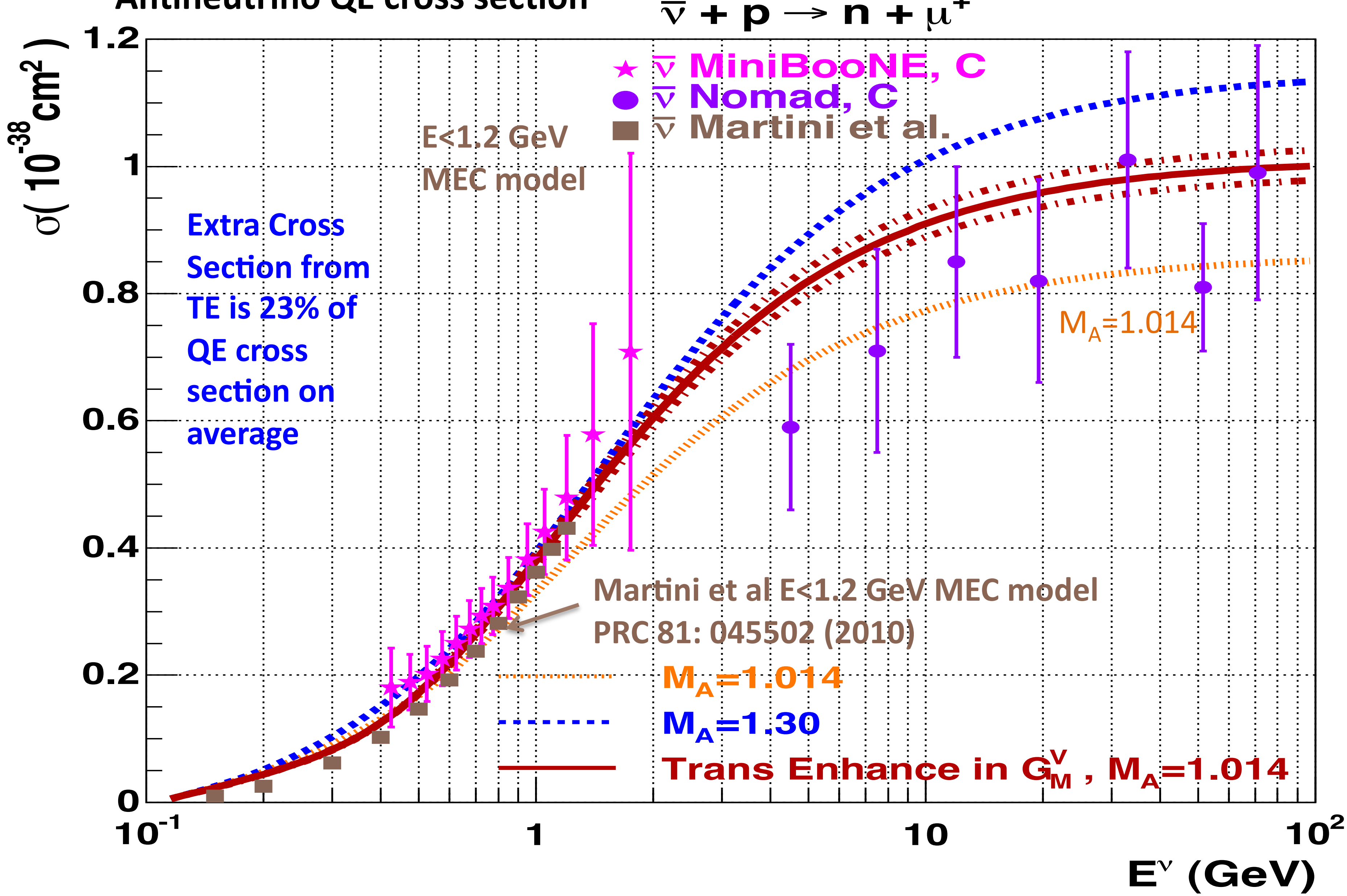
$d\sigma/dQ^2$ Shape

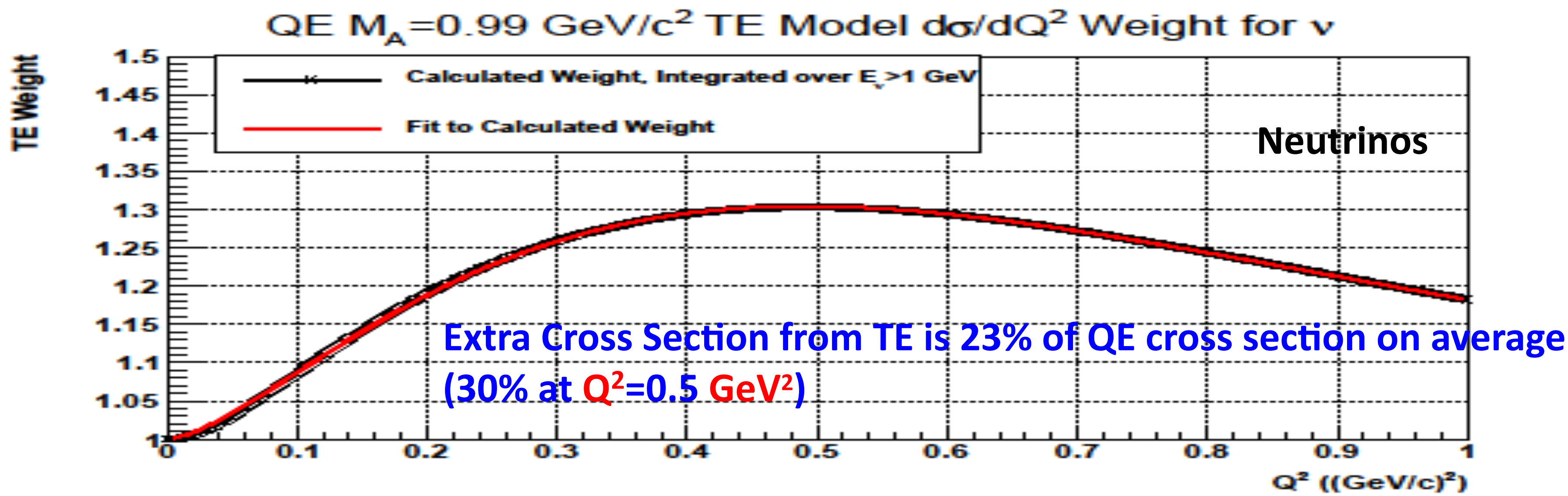
TE model dashed red line - - - - - - - - -




Neutrino QE cross section
ν + n → p + μ⁻
σ(10⁻³⁸cm²)
Eᵛ (GeV)
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

Antineutrino QE cross section





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

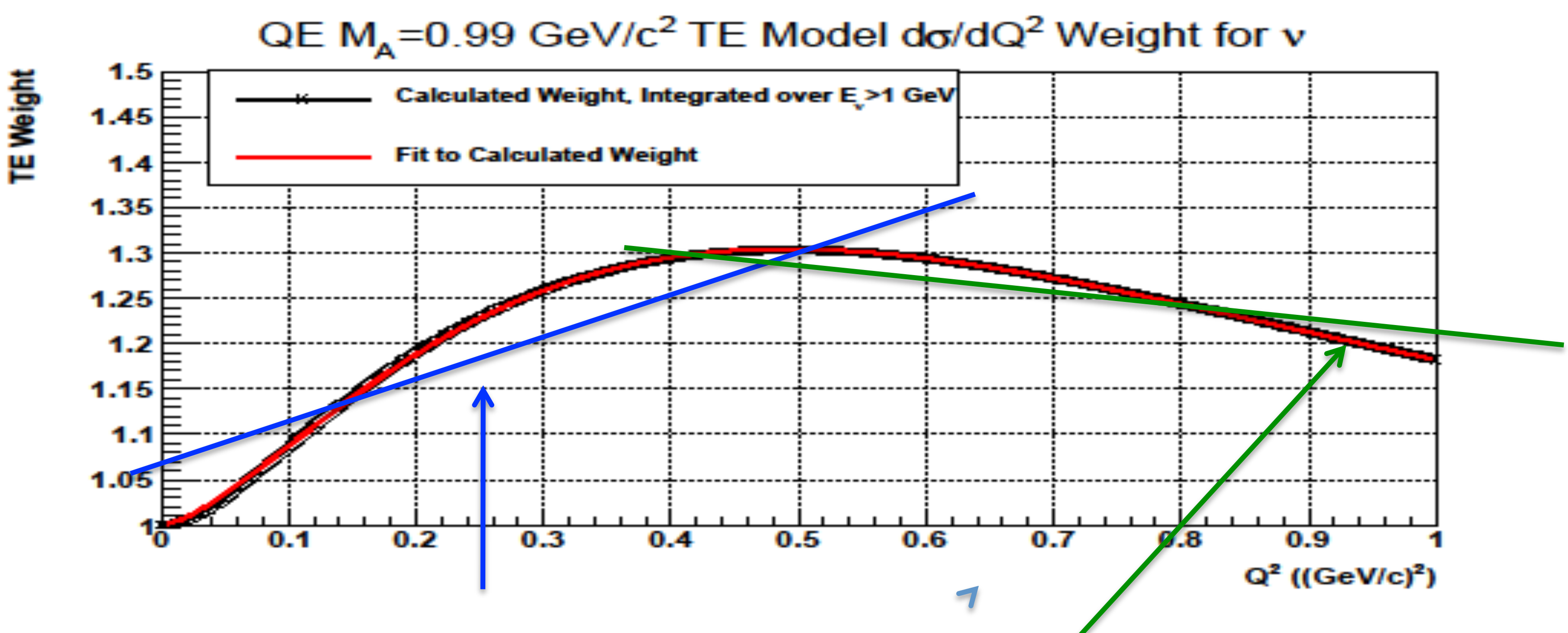
For neutrino energies greater than 1 GeV, the same function describes both neutrinos and antineutrinos (Functional form below is from Ulascan Sarica BS Thesis U of R, 2013).
We can use this functional form to weight GENIE QE events to include TE (this requires no change in GENIE).

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

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

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

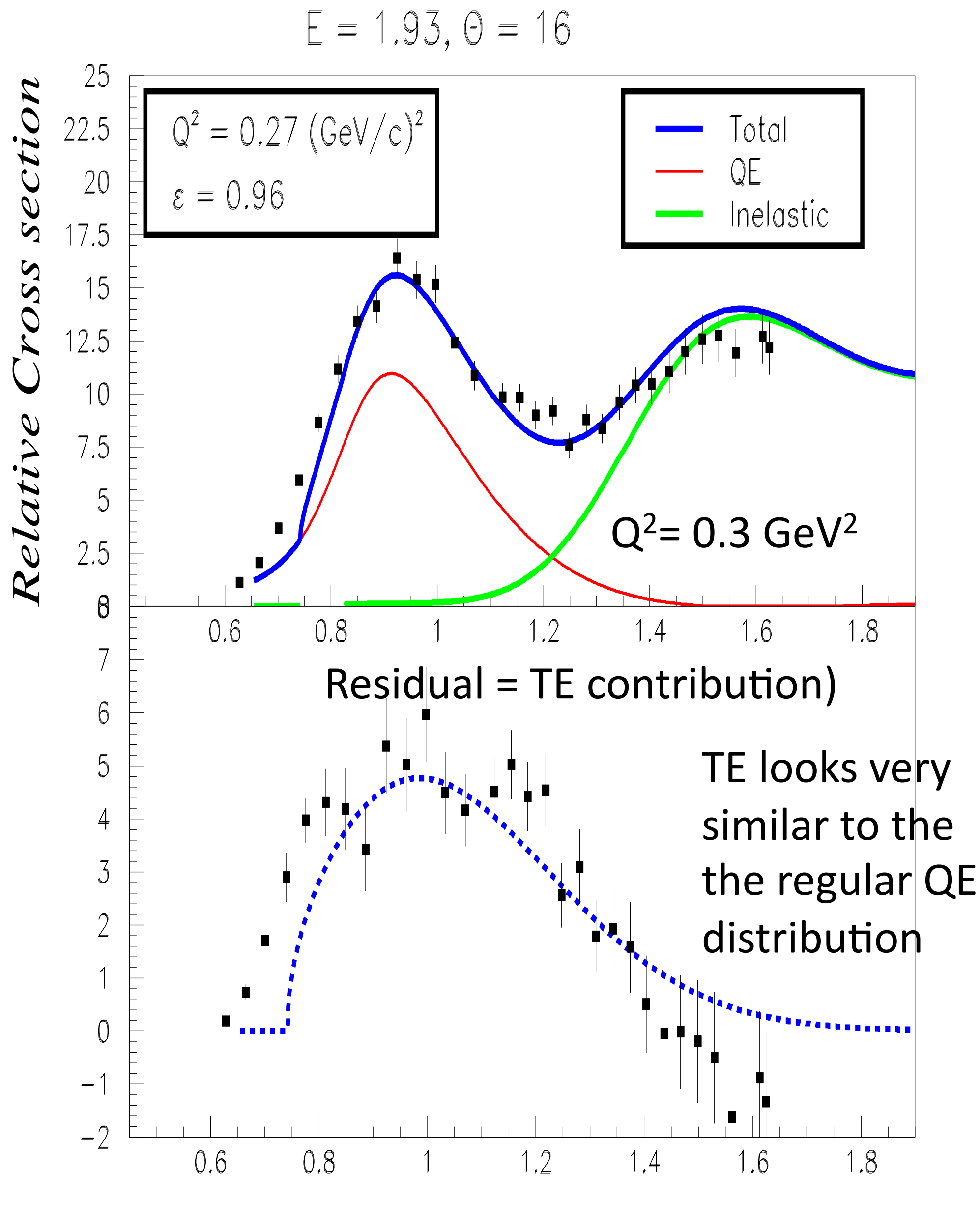
If you include TE, all experiments should get MA=1. What if TE is not included?

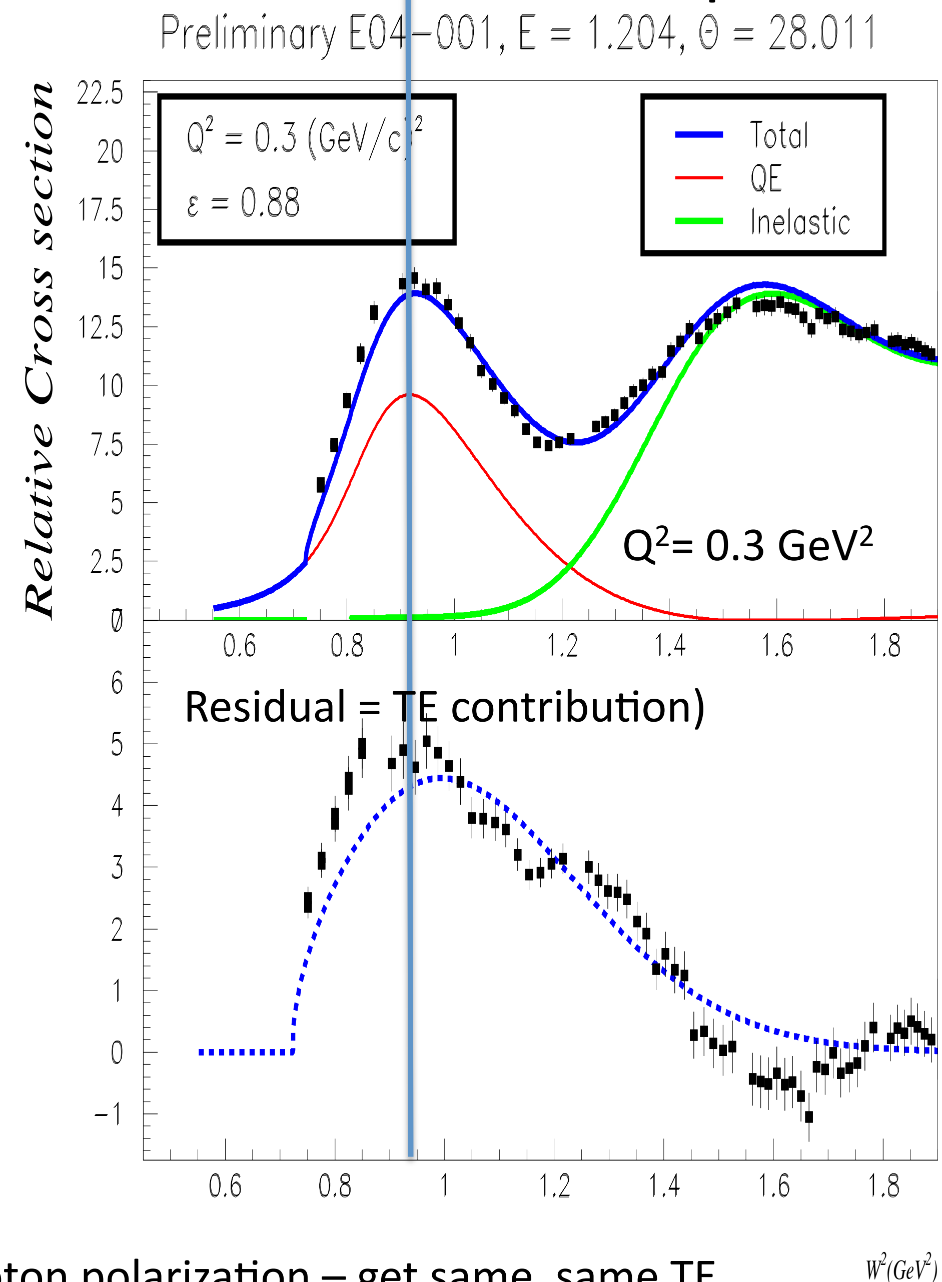


MiniBoone has a low Q2 max, can only fit low Q2. Get MA>1 since the don't include TE

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

We have recently 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

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

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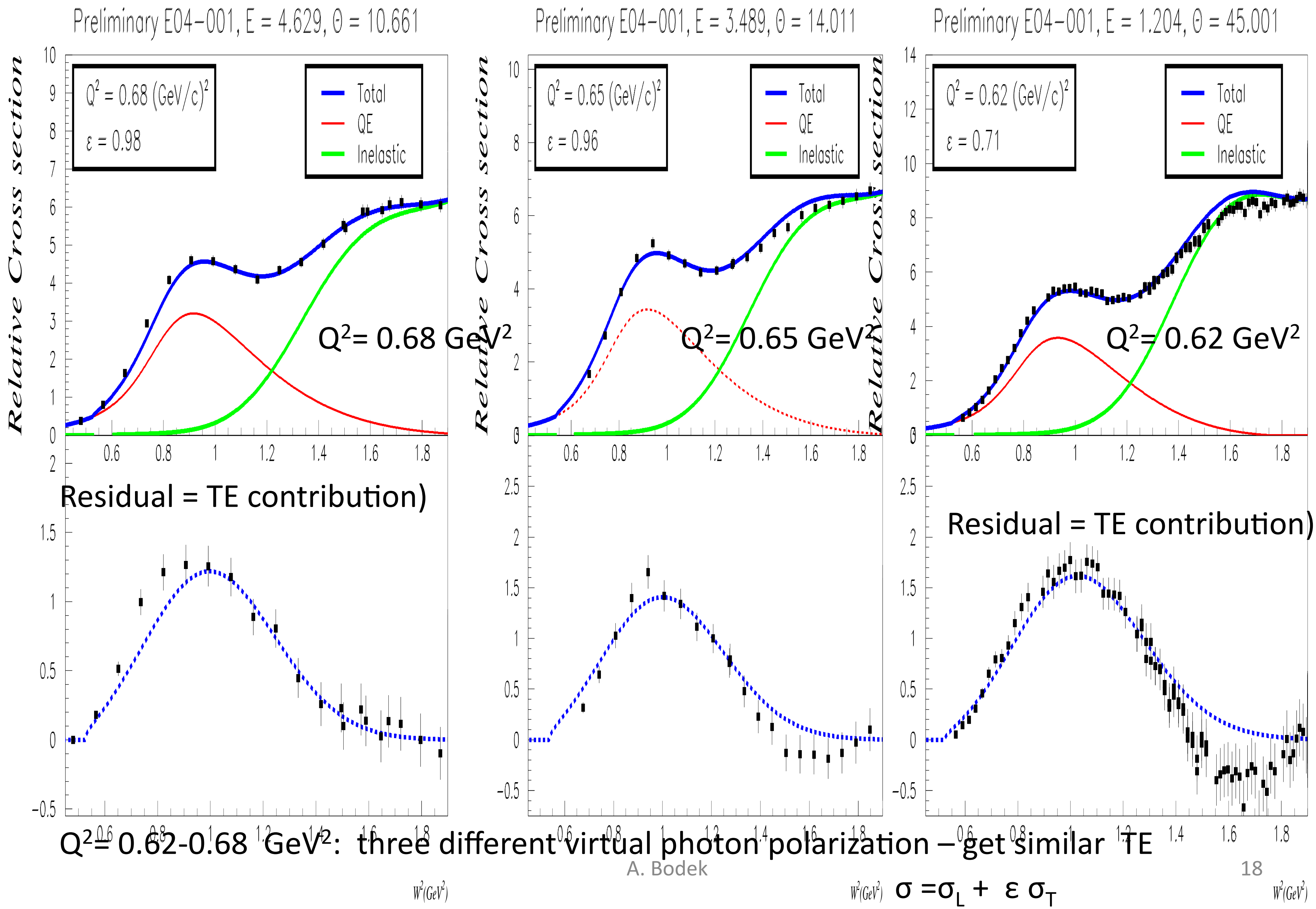
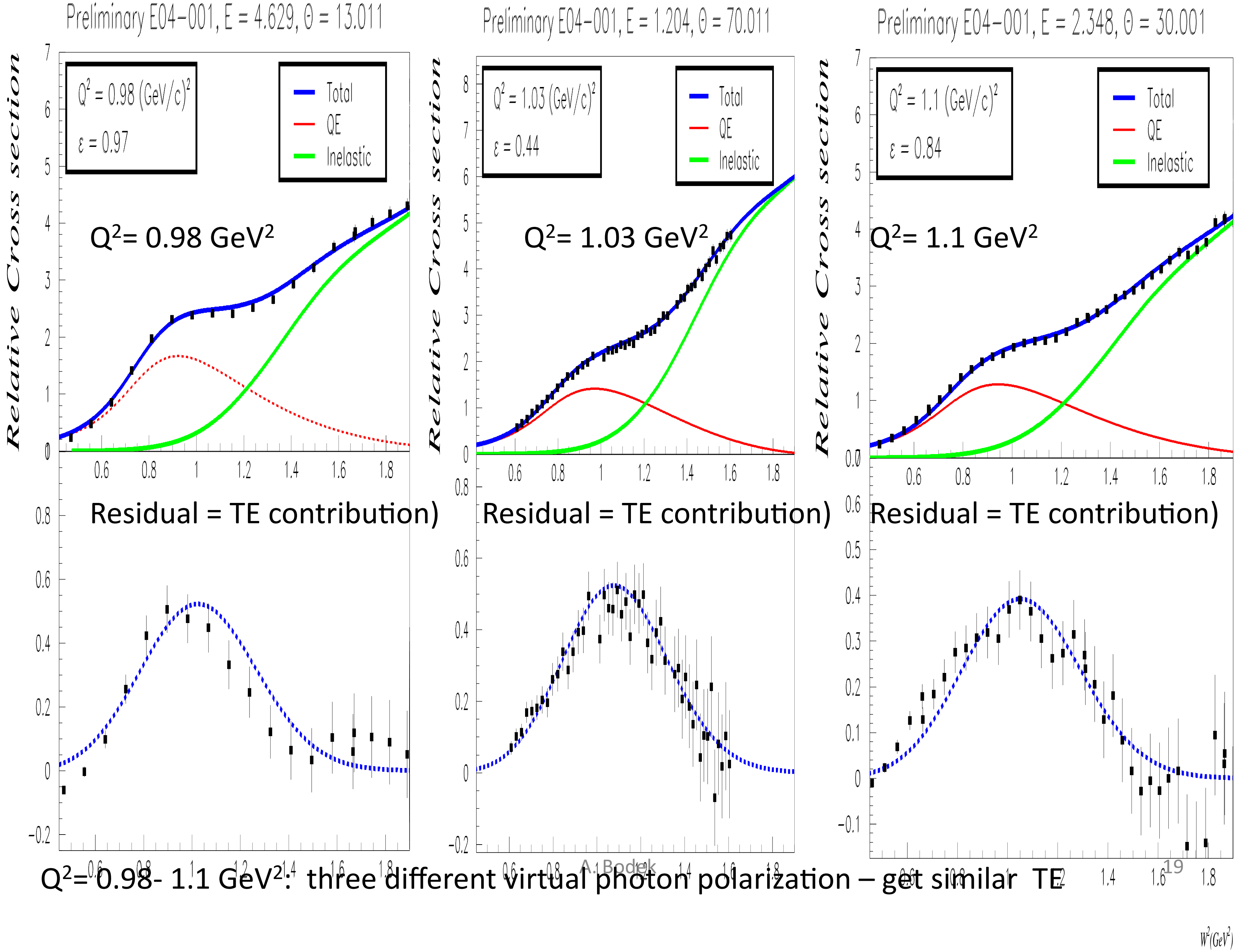


$Q^2 = 0.62\text{-}0.68\ GeV^2$: three different virtual photon polarization – get similar TE

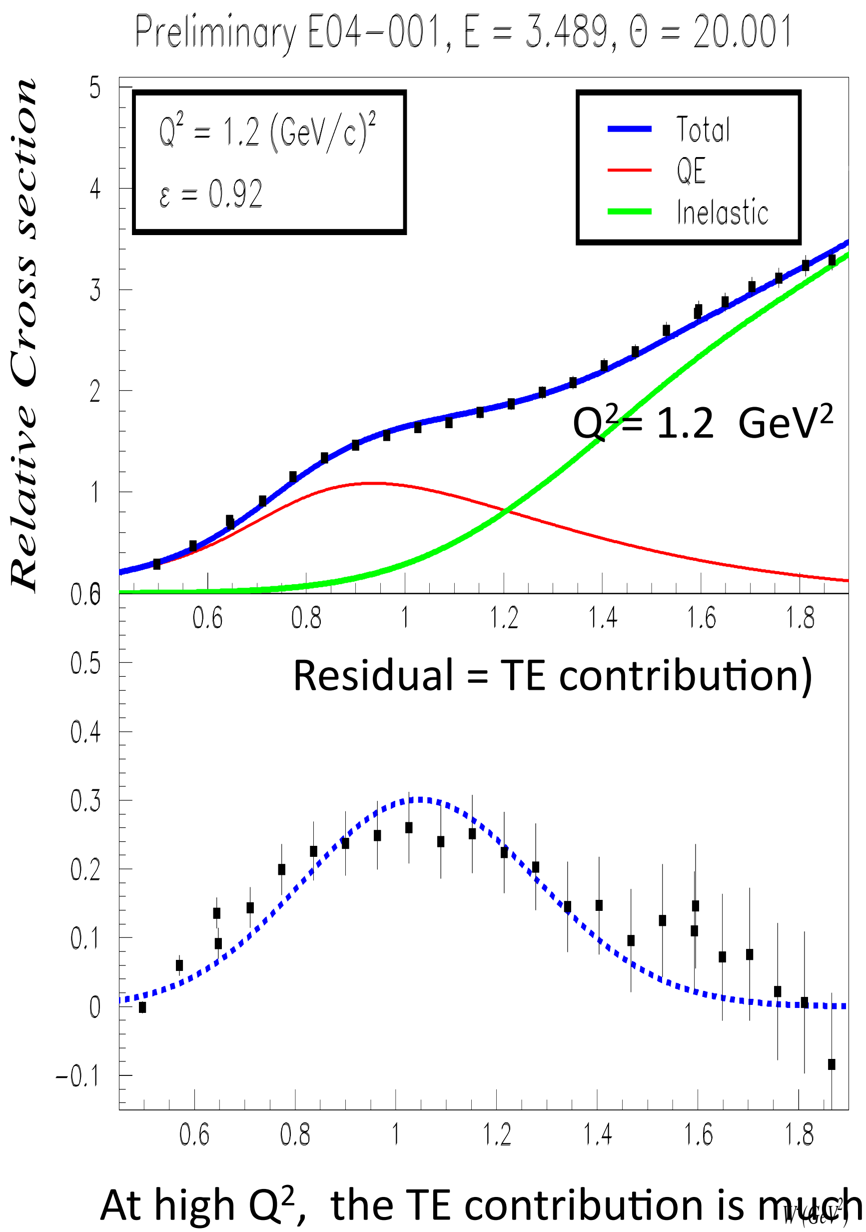
$\sigma = \sigma_L + \varepsilon\, \sigma_T$

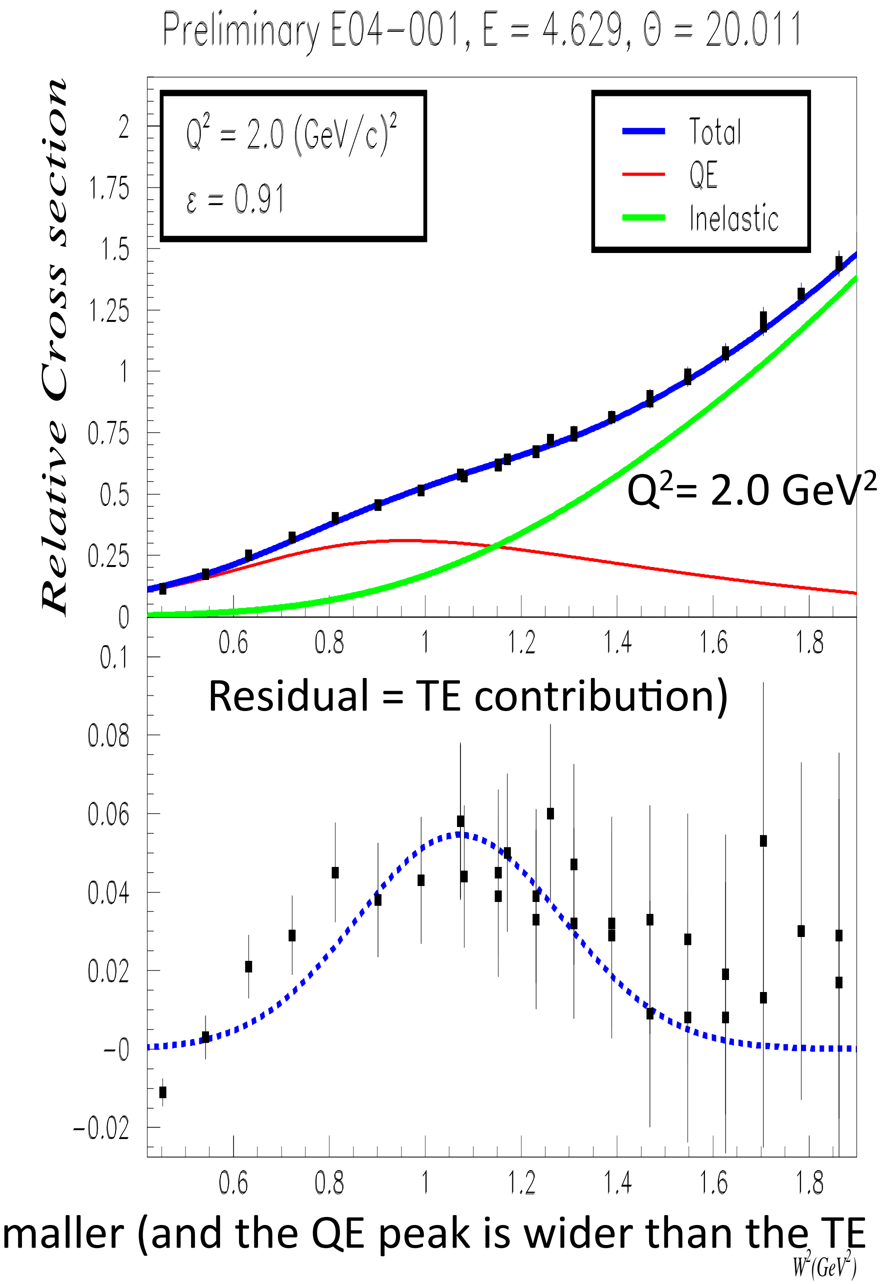
$\sigma = \sigma_L + \varepsilon \sigma_T$



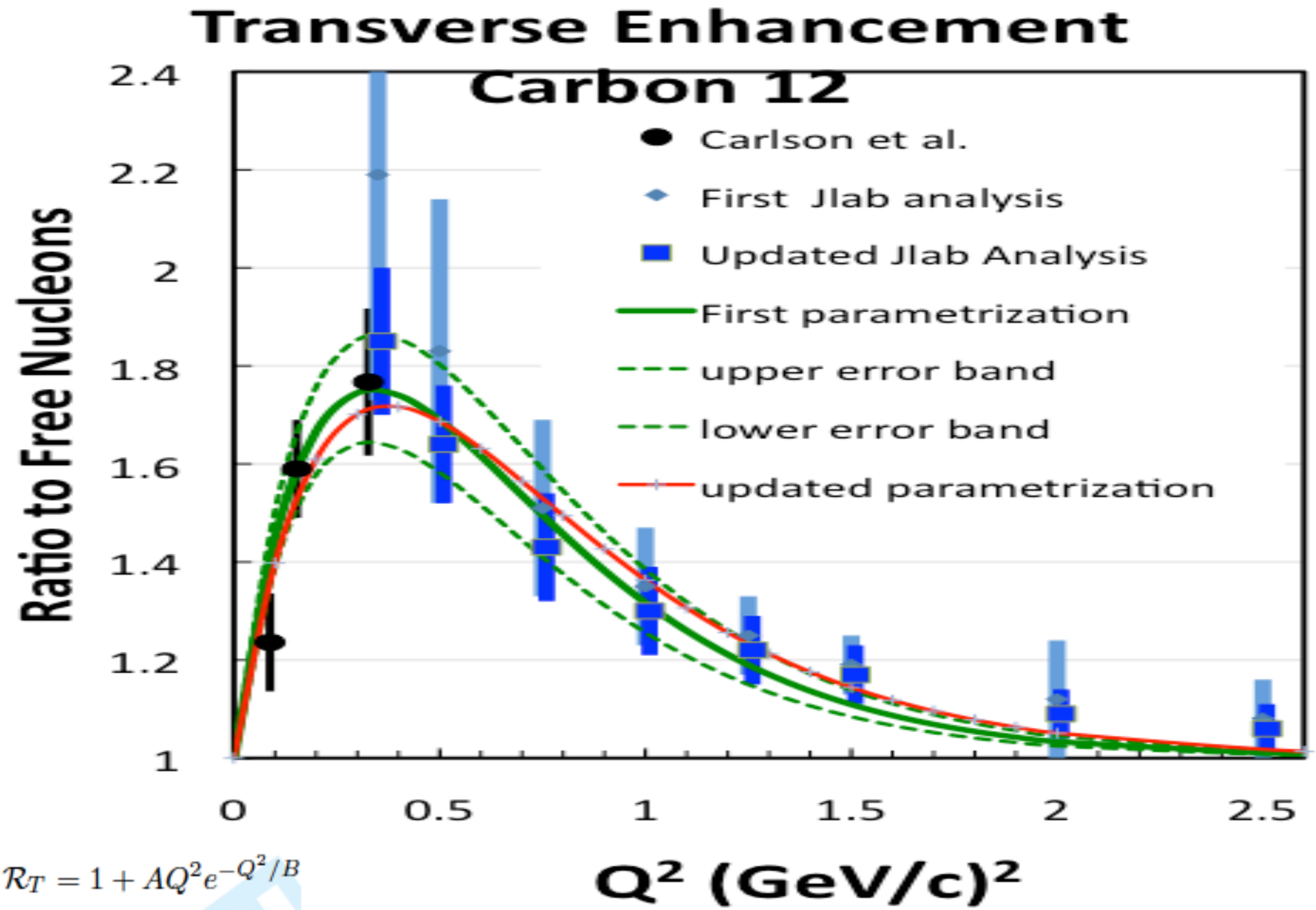
Q²= 0.98- 1.1 GeV²: three different virtual photon polarization – get similar TE

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





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

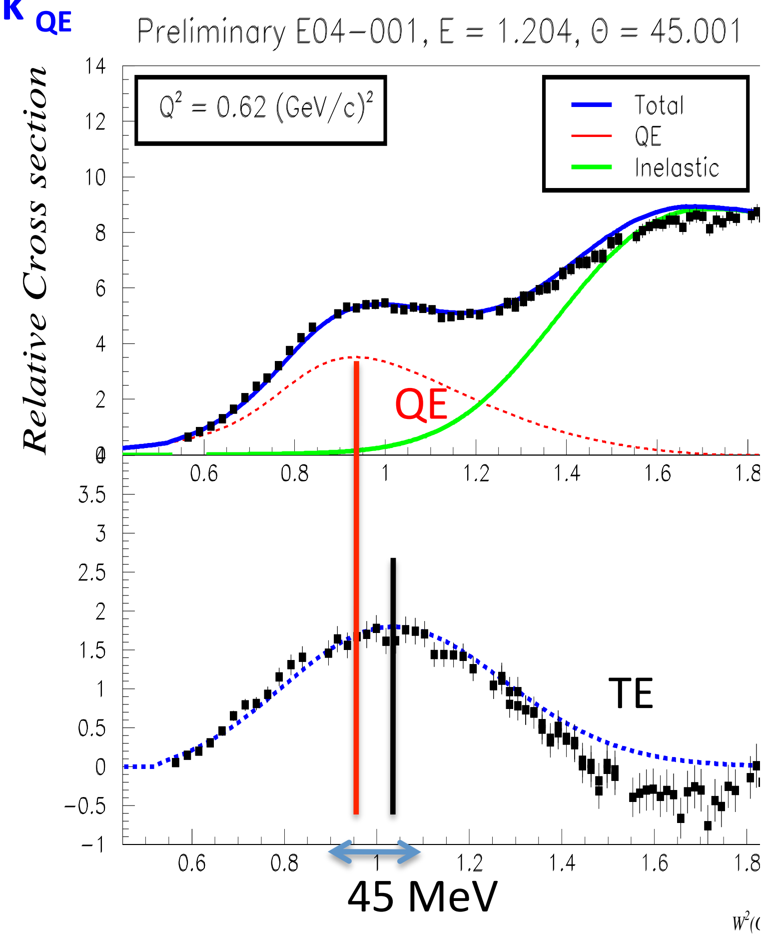
Ratio to free nucleons FROM NEW FITS IN BLUE (In these fits, the longitudinal contribution has been assume to have no enhancement).

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 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

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

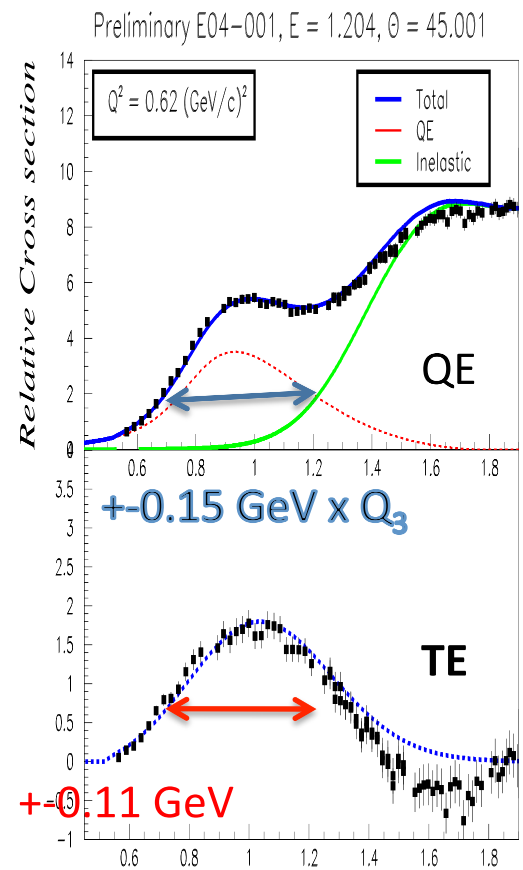


•Difference is 45 MeV.

•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)

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

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

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

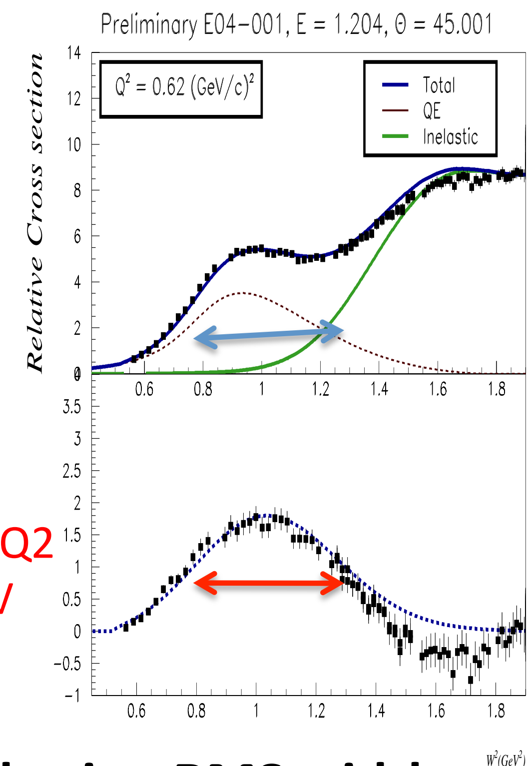
$\{\nu \text{ RMS}\} = \langle k*q_3/M\rangle = Q_3\langle k\_z\rangle/M$

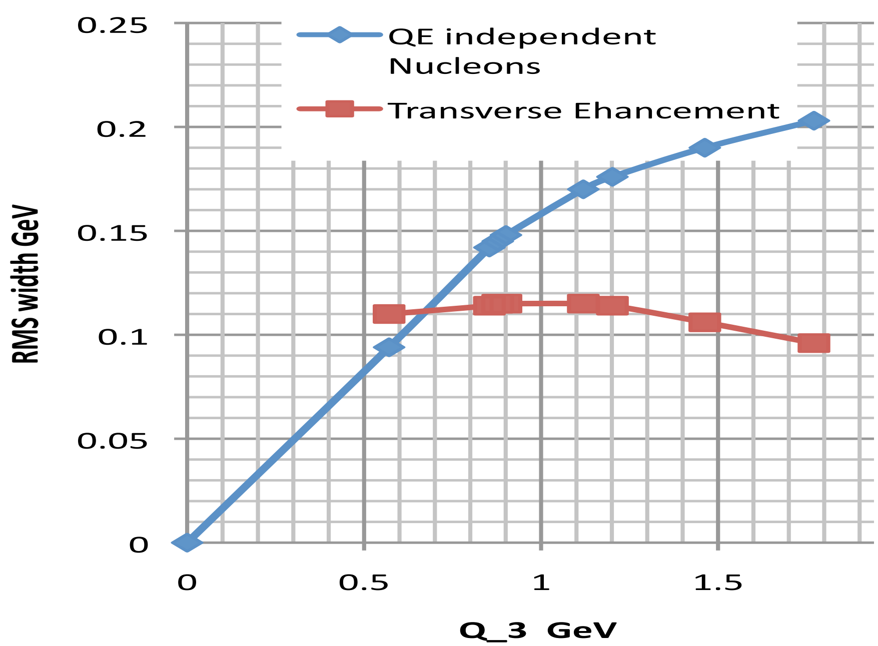
With $Q_3 = \text{sqrt}\{Q^2 (1+ Q^2/4M^2)\}$
expect RMS increases with q3 with a slope of K_3/M

Where 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
RMS = +-0.1 GeV





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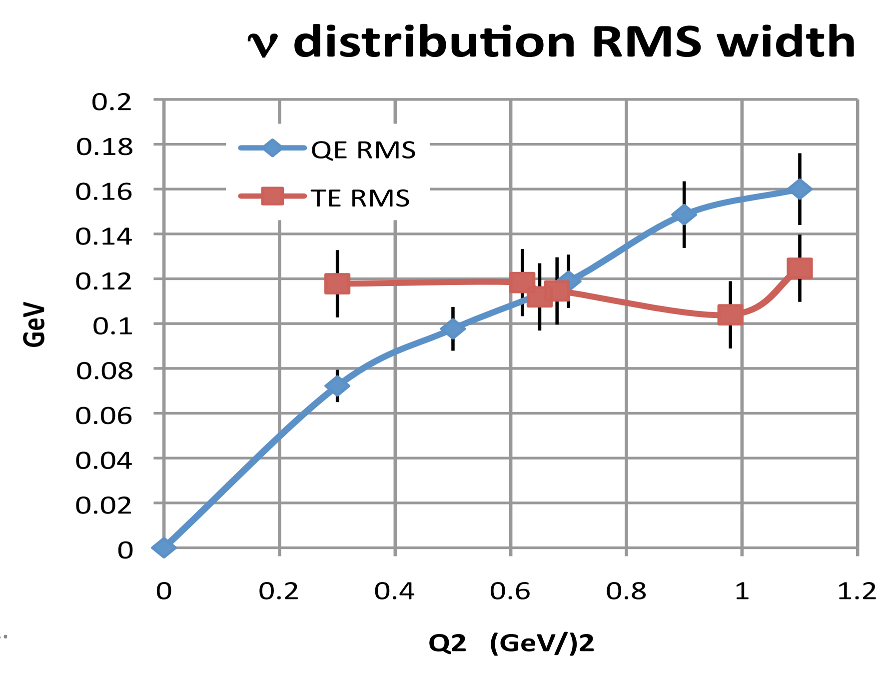
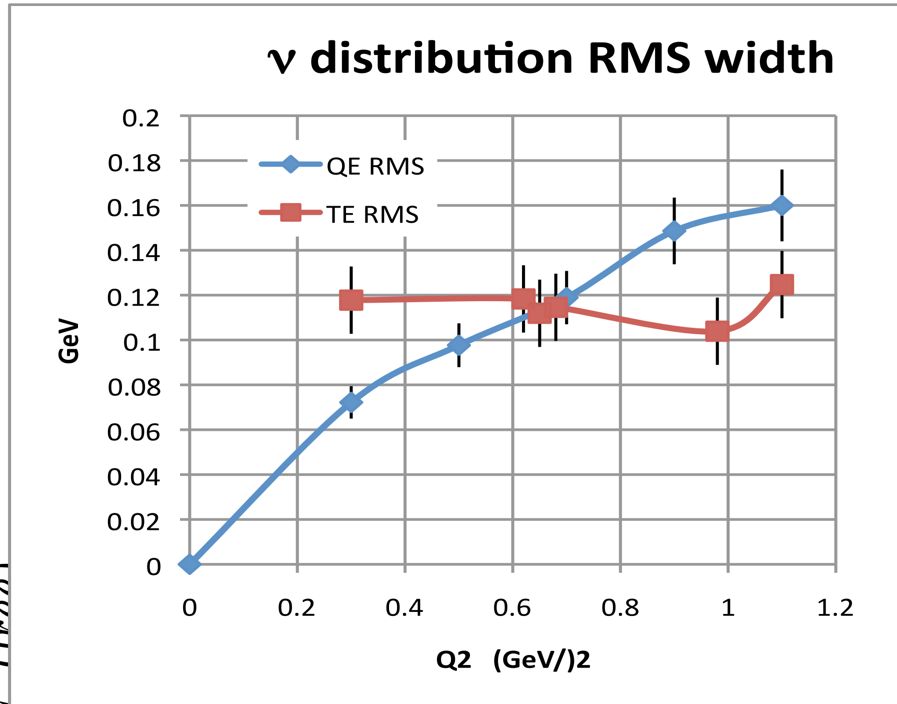
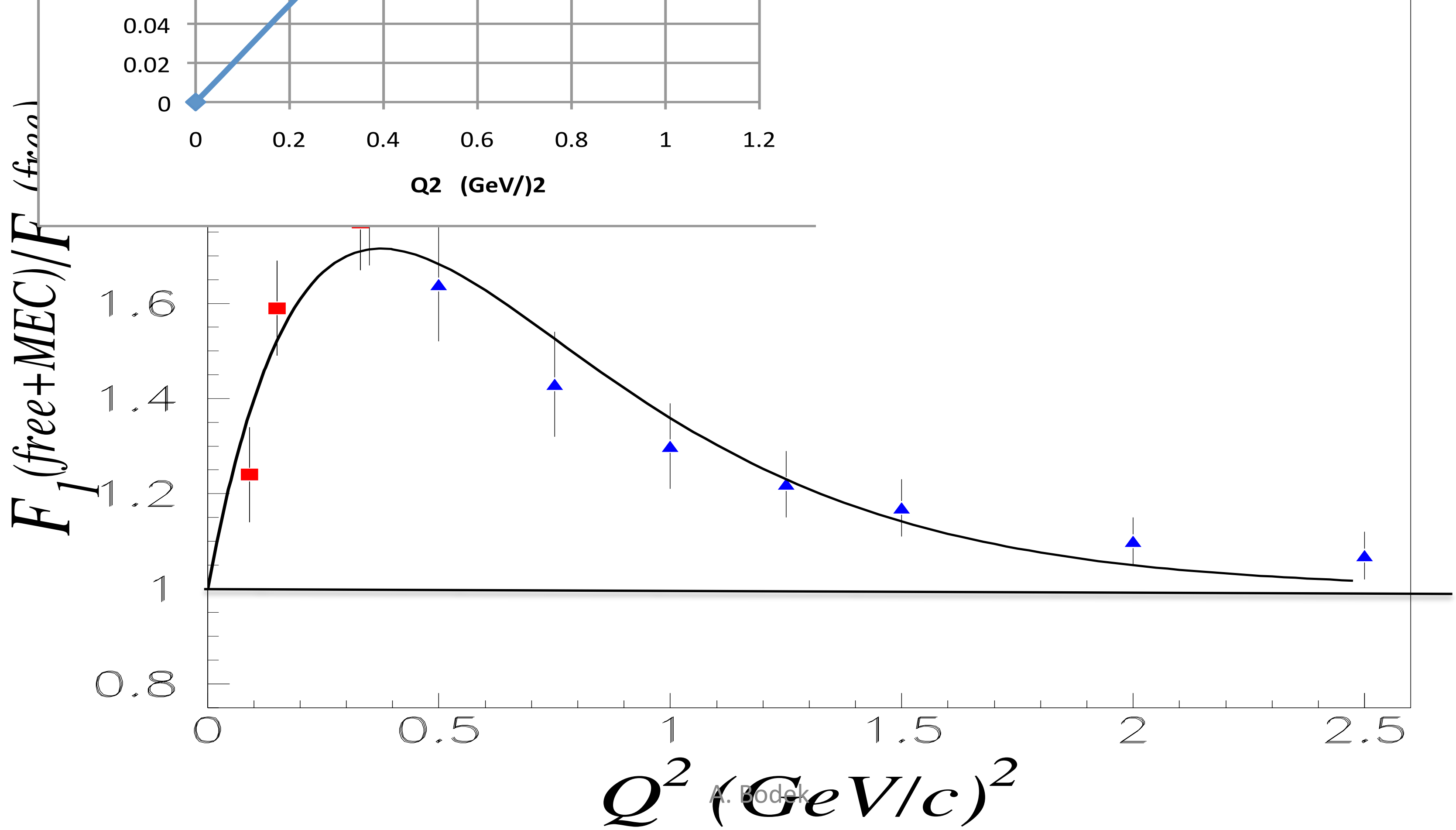






However, on average the RMS width of the QE components and the TE components are similar over the range where TE is significant.

Conclusions on TE

- We have updated the analysis of the $\mathbf{Q^2}$ dependence of TE. The updated analysis has smaller error bars and yields somewhat lower TE contribution vs $\mathbf{Q^2}$. 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$\boldsymbol{\sigma}_{\mathbf{QE}}$. This can be included in Neutrino MC generators by a simple $\mathbf{Q^2}$ dependent weight. The $\mathbf{Q^2}$ 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 $\mathbf{Q^2}$.

- **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.

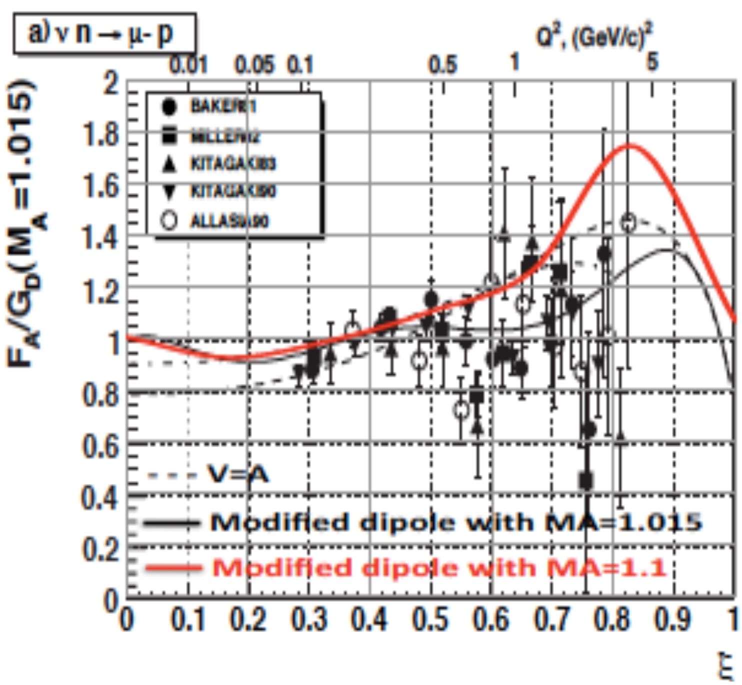
This is the reason why the simple assumption that TE can be described as increasing the effective magnetic form factors of bound nucleons works reasonably well. However, some deviations from the predictions of the enhanced magnetic form factor model are expected

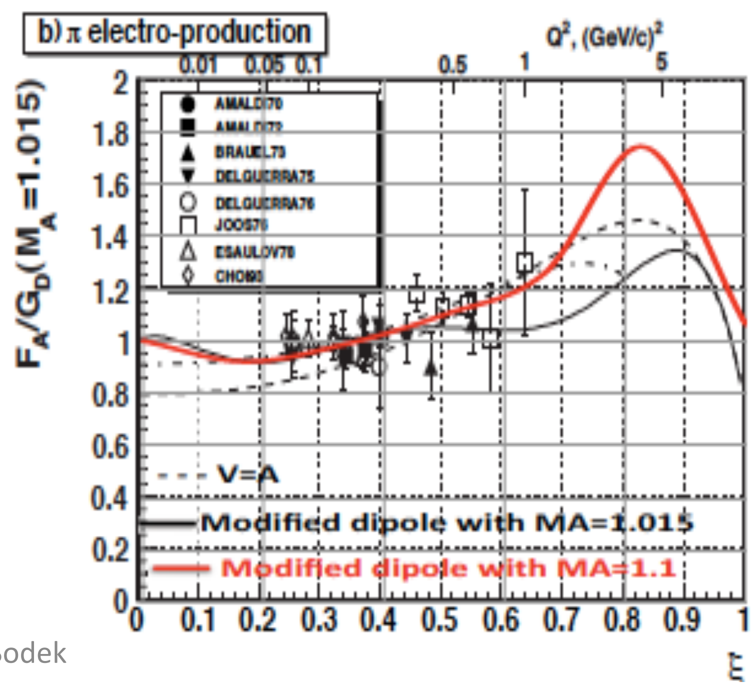
- We are currently extending the analysis lower $\mathbf{Q^2}$ (< 0.3 GeV2) to overlap with our analysis of the low $\mathbf{Q^2}$ L-T separated results from Carlson et al.
- These precise electron scattering data provide a benchmark against which microphysical MEC models (such as 2p2h) can be tested.

Comparison to MiniBooNE data to TE model (Bodek et. al arXiv:1207.1247).

Fit MiniBooNE dv/Q^2 to axial form factor F_A with variable M_A.

- With no TE included in the fit get M_A =1.41+-0.03
- With TE included in the fit get M_A =1.17 +-0.03
- With TE included and modified dipole form M_A =1.09 +-0.03,.
- The fit (red line) is consistent with F_A from neutrino data on Deuterium (left) and F_A from pion electroproduction data (on right) for Q^2<1 GeV ^{2}.





Can we determine if extra nucleons are associated with TE?

- Note that because of final state interactions (FSI), about 50% of QE events have extra nucleons in the final state. Experiments at Jefferson Lab indicate that extra nucleons are predominantly from FSI.
- The high momentum components of the wave function originate from short range correlations (SRC). About 20% of events come from short range correlations. Therefore, an additional 20% of the events should have a low energy spectator nucleon from SRC. These were observed at Jlab (with great difficulty) at high values of Q^2 .
- If the 23% TE contribution also come with an extra nucleon, it would would be difficult to differentiate from the extra nucleons from FSI, or the spectator extra nucleon from SRC. One way to study this is via the Q^2 dependence of the fraction of event with extra nucleons (since TE is Q^2 dependent).
- The TE model for neutrino scattering assumes that these three processes (QE+FSI, SRC and TE/MEC) cannot be differentiated from which other. Therefore, they should interfere with each other and this could be modeled by an effective nuclear modification of the magnetic form factor for a bound nucleon. This also implies that TE interferes with the QE axial current. The approximation is good on average but it does not account for the Q^2 dependent modifications of the shape.
- The predictions of the TE model are in reasonable agreement with both the total QE cross sections and Q^2 distributions. This indicate that the approximation works reasonably well.

Extra Slides

Why is it that the failure of the independent nucleon model in transverse scattering was not emphasized before.

1. *Early electron experiments were at low Q2 (Q2<0.2 GeV2) and small angles. At small angles and low Q2 the cross section is dominated by longitudinal scattering. Therefore, the effect was not observed. In this region, the independent nucleon Fermi gas model appeared to work reasonably well since the cross section was mostly longitudinal.*

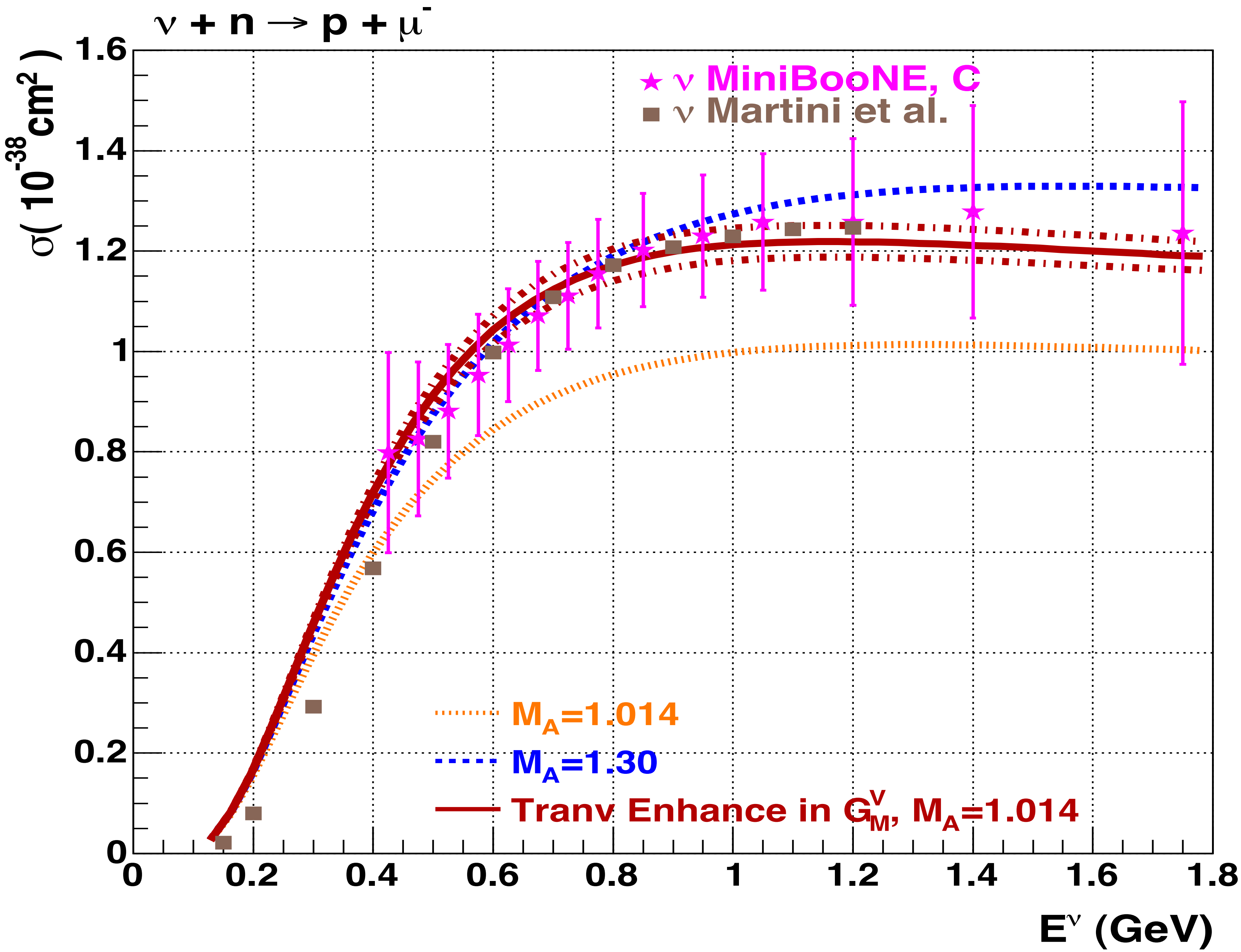
2. *The transverse enhancement is small both at very low Q2 and also at large Q2 (e.g. Q2>1.5 GeV2) . More recent electron scattering experiments focused on large Q2, were the effect is also small. In the high Q2 region, the independent nucleon Fermi gas model also appears to work reasonably well (with the inclusion of high momentum components from two nucleon correlations).*

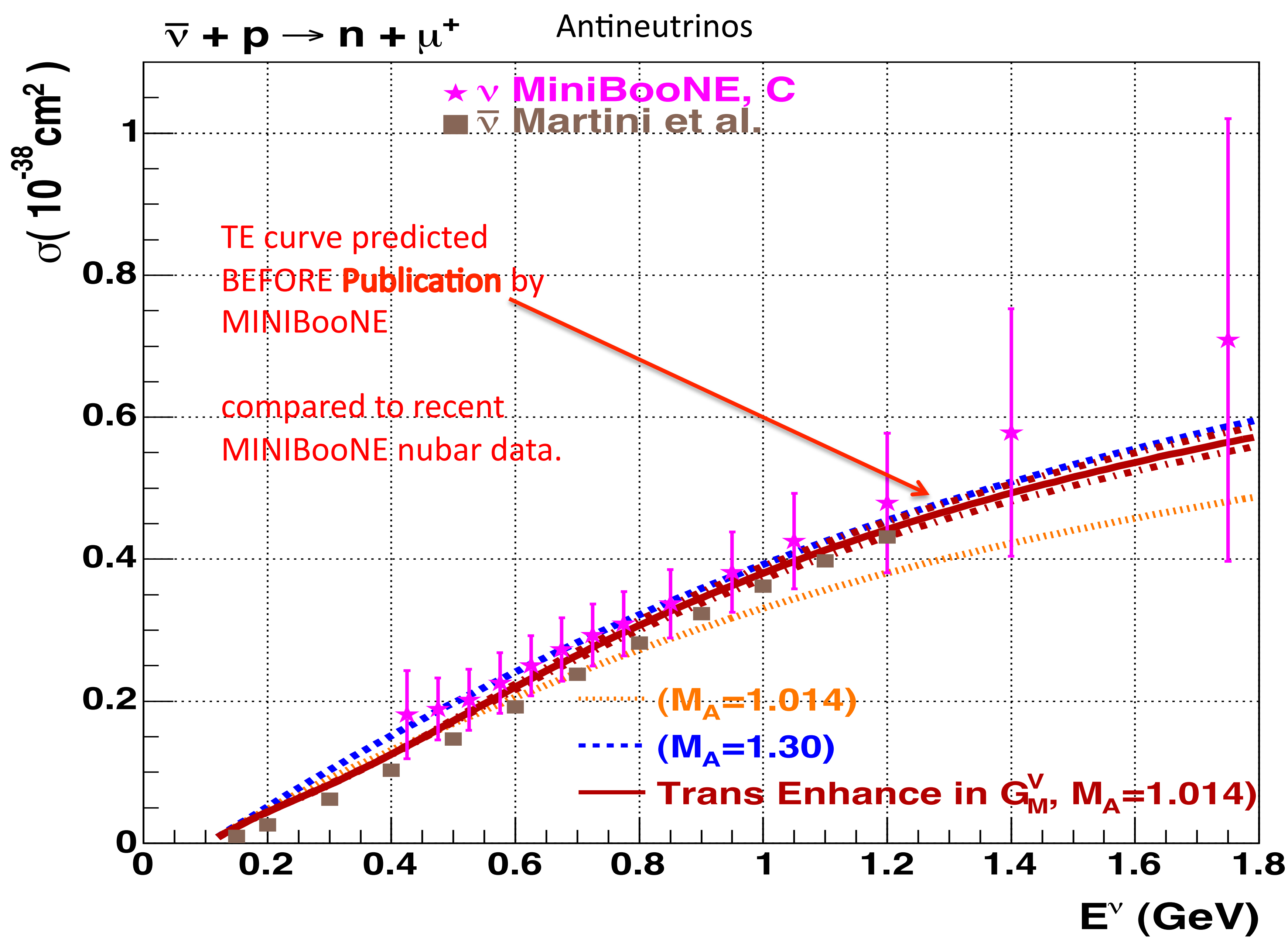
Therefore, regions where the Transverse Enhancement (which has been attributed to Meson exchange currents) is significant were avoided (e.g. for studies of two nucleon correlations etc).

Radiative correction

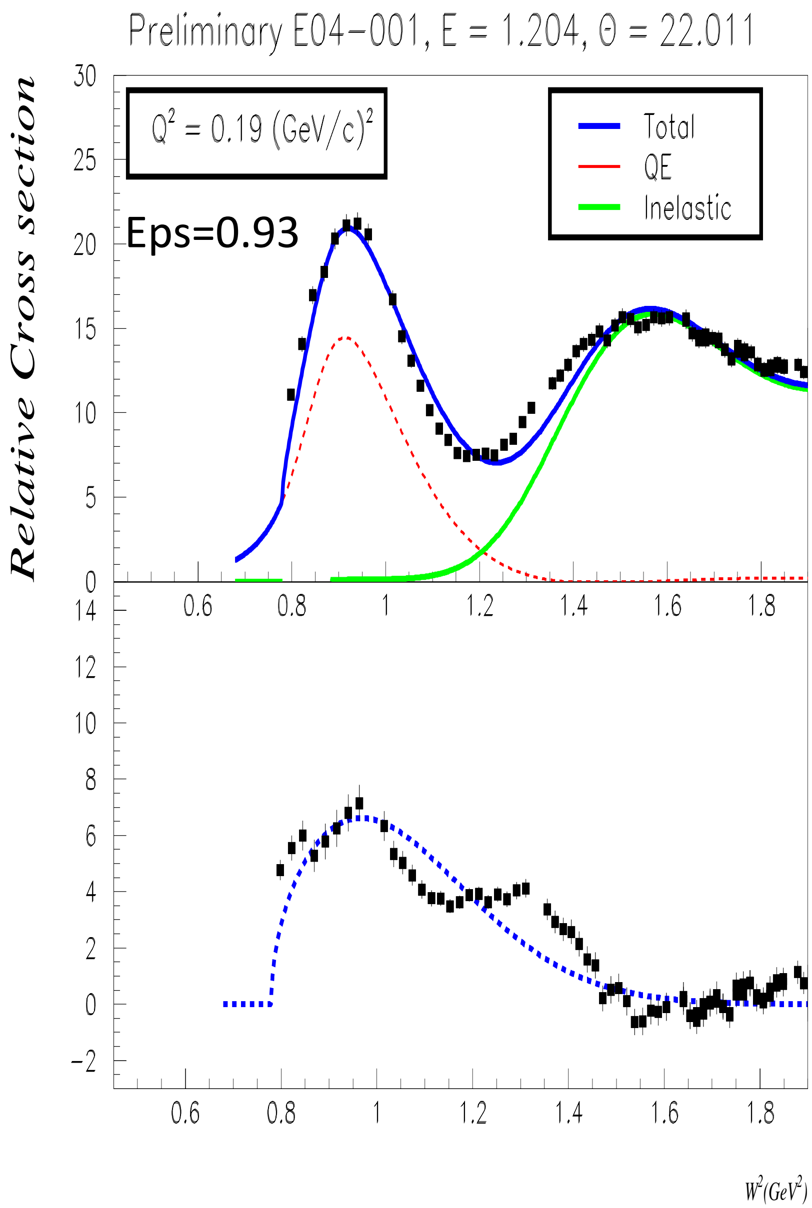
However, in electron scattering, the contributions of the transverse enhancement as a function of **Q^2** has to be investigated for purely technical reasons.

This is because in order to do radiative corrections (e.g. for measurements of resonance and inelastic vector structure functions in JUPITER/Jefferson Lab) we need to know the cross section everywhere, including the QE region. Therefore, we need to have fits that include the contribution of TE at all Q2.


ν + n → p + μ⁻
σ(10⁻³⁸cm²)
E^ν (GeV)
ν MiniBooNE, C
ν Martini et al.
M_A=1.014
M_A=1.30
Tranv Enhance in G^V_M, M_A=1.014
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8



$\bar{\nu} + p \rightarrow n + \mu^+$
Antineutrinos
ν MiniBooNE, C
$\bar{\nu}$ Martini et al.
TE curve predicted
BEFORE Publication by
MINIBooNE
compared to recent
MINIBooNE nubar data.
$(M_A=1.014)$
$(M_A=1.30)$
Trans Enhance in G_M^V, $M_A=1.014$)
$\sigma(10^{-38}cm^2)$
E^ν (GeV)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8



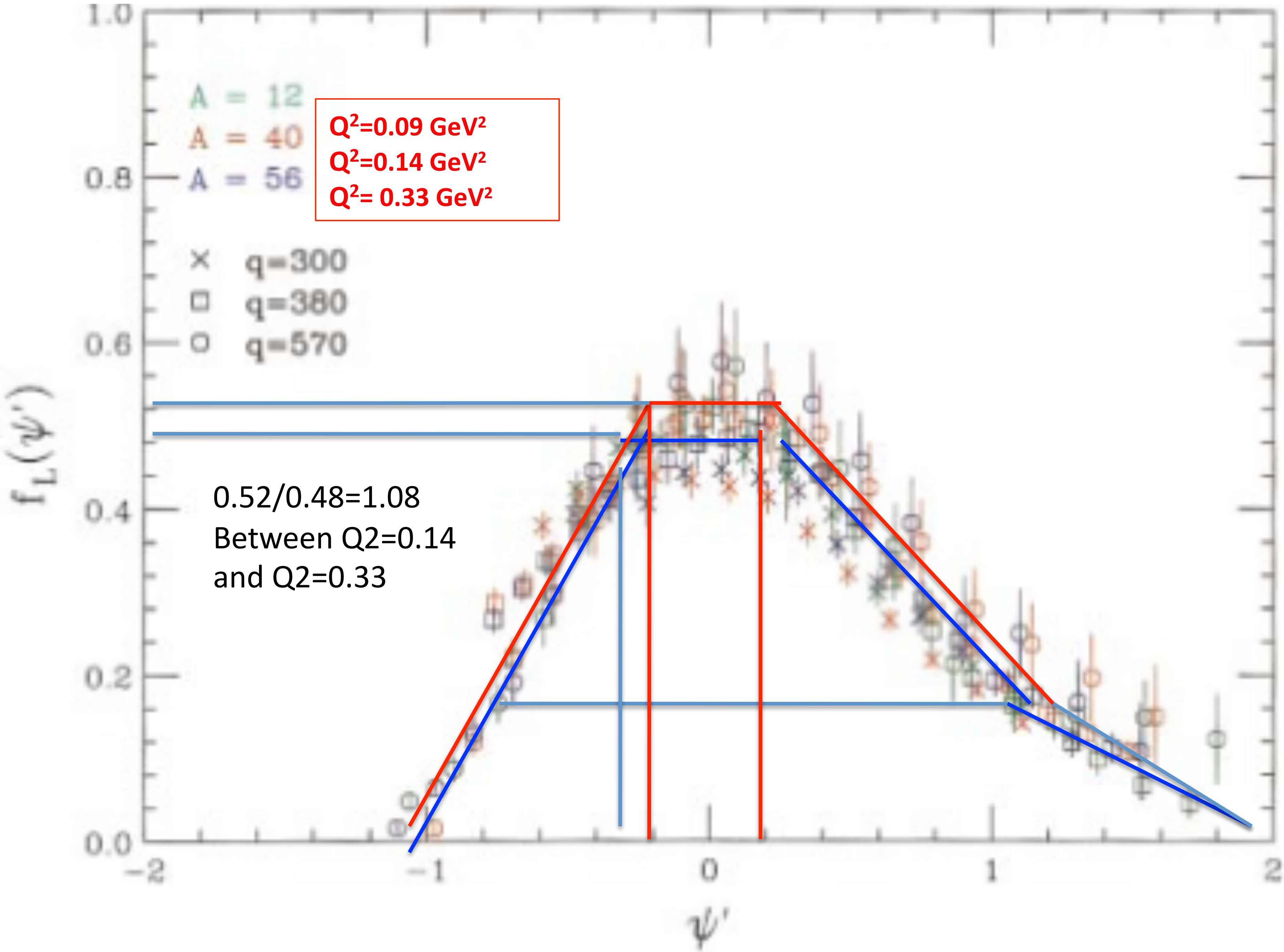
Q^2_QE	E	theta	eps
0.19	1.2	22	0.93
0.3	1.2	28	0.88
0.62	1.2	45	0.71
0.65	3.5	14	0.97
0.68	4.6	10.66	0.98
0.98	4.6	13.0	0.97
1.0	1.2	70.0	0.44
1.1	2.3	30.0	0.84
1.2	3.5	20.0	0.92
2.0	4.6	20.0	0.91

Investigation of the width of the TE contribution vs Q^2

Q^2 GeV^2	TE RMS width in W^2 GeV^2	error
0.3	0.221	0.010
0.62	0.222	0.010
0.65	0.210	0.010
0.68	0.215	0.010
0.98	0.195	0.010
1.1	0.234	0.010
Average	0.216	

Unlike free nucleon QE scattering, with width of the TE distribution in W^2 appears to be independent of Q^2 and is about 215 MeV

0.215 GeV2 RMS width in W2 corresponds to a 0.115 GeV RMS width in energy transfer (ν).



1.0
0.8
0.6
0.4
0.2
0.0
−2
−1
0
1
2
A = 12
A = 40
A = 56
Q2=0.09 GeV2
Q2=0.14 GeV2
Q2= 0.33 GeV2
q=300
q=380
q=570
f_L(ψ')
ψ'
0.52/0.48=1.08
Between Q2=0.14
and Q2=0.33