Inclusive Electron Scattering and neutrino scattering

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University of Rochester

Hall C User Meeting

Saturday, January 14, 2012

2:00-2:30 pm

Neutrino Experiments

- The field of neutrino oscillation physics has progressed from the discovery of neutrino oscillation to an era of precision measurements of mass splitting and mixing angles.

- A reliable model of neutrino inelastic cross sections at low energies is essential for precise neutrino oscillations experiments. At the far detectors, one compares the observed neutrino cross sections to the expected neutrino cross section. Relevant range of interest is 0.3-10 GeV.

Modeling neutrino cross sections

- The cross sections for various final state (in a nuclear target) need to be known, since neutrino detectors have different response for protons, slow protons, nuclear fragments, neutrons and pions (the energy of the neutrino is inferred from the energy of the reconstructed final state).

- Therefore, modeling both cross sections and final state interactions is important.

- Having both a near detector and far detector helps, but the neutrino spectrum in the near and far detectors are different. Some experiments such as large water Cerenkov detectors (e.g. T2K) do not have a near detector, and compare their data to the "Predicted" cross sections without oscillations.

Vector Structure Functions and Form Factors

- If the isospin of the initial and final states are known, one can express the vector structure functions (or form factors) in neutrino scattering in terms of the corresponding structure functions in electron scattering (in nuclear targets)

- In addition, nuclear effects need to be modeled because neutrino detectors use massive nuclear targets (e.g. Water (T2K) , Iron (MINOS) , Scintillator (NOVA) , liquid Argon (future)

Do electron scattering measure everything that is needed?

- Neutrino scattering have a vector and axial-vector components, as well as axial-vector interference. Only the vector part can be measured in electron scattering.

- For free quarks at high Q^2, V=A. At low Q^2, axial current is only partially conserved. For QE and resonance production, there are Bubble chamber experiments (H and D) that give some information on the axial form factors.

Neutrino Reaction Final States

1. Quasielastic scattering (W<1.07)
2. Delta production region 1.06<W<1.4
3. Higher resonances region 1.4<W<1.9
4. Inelastic Scattering W>1.9
5. Coherent processes on nuclear target such as coherent pion production (W<0.938).

Studies of interest to neutrino physicists are basically studies in nuclear physics. What happens in nuclei.

Modeling Neutrino Inelastic Scattering

Resonance region, quasielastic and coherent processes are modeled separately

- Vector Structure Function F2 on H and D is well modeled at all Q^2 by the Bodek-Yang Model, which uses modified GR98 PDFs. These are obtained from fits to F2 (electron/muon) for all DIS data, including photo-production data.
- A simple fit to EMC effect/Nuclear shadowing is used. Need: W and Q^2 dependence of nuclear effects (EMC effect/Shadowing) (From electron scattering)
- Need: (from electron/muon scattering) is a good parameterization of R that works down to $Q^2=0$ (on nuclear targets).
- Fragmentation functions to model final state (from electron/muon scattering)
- Model FSI in nuclear targets (based on electron/muon scattering)
- In addition, we need additional corrections because Axial not equal to Vector at small Q^2. (not provided by electron scattering – use available neutrino data and wait for more neutrino data)

Sensitivity to R within Bodek-Yang Model

The neutrino (antineutrino) differential cross section, is given by:

$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 ME}{\pi}\Big(\Big[1 - y(1+\frac{Mx}{2E}) + \frac{y^2}{2} \times \Big(\frac{1+(\frac{2Mx}{Q})^2}{1+\mathcal{R}}\Big)\Big]\mathcal{F}_2 \pm \Big[y - \frac{y^2}{2}\Big]x\mathcal{F}_3\Big) \quad (48)$$

The integrated cross sections extracted from the above equation can be approximately expressed in terms of (on average) the fraction antiquarks $f_{\bar{q}} = \overline{Q}/(Q+\overline{Q})$ in the nucleon, and (on average) the ratio of longitudinal to transverse cross sections $\mathcal{R}$ as follows: In QPM F2=(Q+Qbar), xF3=(Q-Qbar)

$$\sigma(\nu N) \approx \frac{G_F^2 ME}{\pi}(Q+\overline{Q})\Big[(1-f_{\bar{q}}) + \frac{1}{3}f_{\bar{q}} - \frac{1}{6}\mathcal{R}\Big], \quad (49)$$

and

$$\sigma(\overline{\nu} N) \approx \frac{G_F^2 ME}{\pi}(Q+\overline{Q})\Big[\frac{1}{3}(1-f_{\bar{q}}) + f_{\bar{q}} - \frac{1}{6}\mathcal{R}\Big], \quad (50)$$

With $\langle \mathcal{R} \rangle = 0.2$ and $\langle f_{\bar{q}} \rangle = 0.1725$, we obtain $\langle \sigma_{\bar{\nu}}/\sigma_{\nu} \rangle =$ 0.487, which is the world's experimental average value in the 30-50 GeV energy range. The above expressions are used to estimate the systematic error in the cross section originating from uncertainties in $\mathcal{R}$ and $f_{\bar{q}}$ (as shown in Table 3).

Want to know R to +- 0.025 to reduce error to 1%

source	change (error)	change in σ_{ν}	change in $\sigma_{\bar{\nu}}$	change in $\sigma_{\bar{\nu}}/\sigma_{\nu}$
R	+0.10	-2.0%	-4.0%	-2.1%
$f_{\bar{q}}$	+10%	-1.4%	+2.8%	+4.2$
P (K^{axial}_{sea})	+ 0.3	+1%	+2%	+1.0%
N	+3%	+3%	+3%	0
Total		±4.0%	±6.1%	±4.8%

<---- R
<-----Sea antiquarks
<----Axial sea
--PDF normalization quark versus gluon

Error in R leads to large error in the antineutrino cross sections from the inelastic part. Above does not include error from EMC effect/shadowing, or axial valence. Or resonances and QE components of F2.

What do people Use for R in DIS region ?

- K2K, T2K use Callen Gross F2=2xF1 which is equivalent to $R=Q^2/\nu^2$ (not too good)-> Too small. R is larger because of gluons at small x and because of target mass effects are large x.
- Bodek-Yang uses R1998, and no Nuclear Dependence on R K. Abe *et al.*, Phys. Lett. **B452**, 194 (1999)

Plus another factor to make R go to zero at $Q^2=0$

$$\mathcal{R}_{vector}(x, Q^2 < 0.35) = 3.207 \times \frac{Q^2}{Q^4+1} \times \mathcal{R}_{world}(x, Q^2 = 0.35)$$

Measurements of F_2 and $R = \sigma_L/\sigma_T$

on Nuclear Targets in the Nucleon Resonance Region

University of Virginia
August 2010

Vahe Mamyan
Yerevan, Armenia

A Dissertation Presented to the Graduate Faculty of University of Virginia in Candidacy for the Degree of Doctor of Philosophy

E04-001 +(E02-109, E06-009) -- L/T experiment.

First results, not published yet

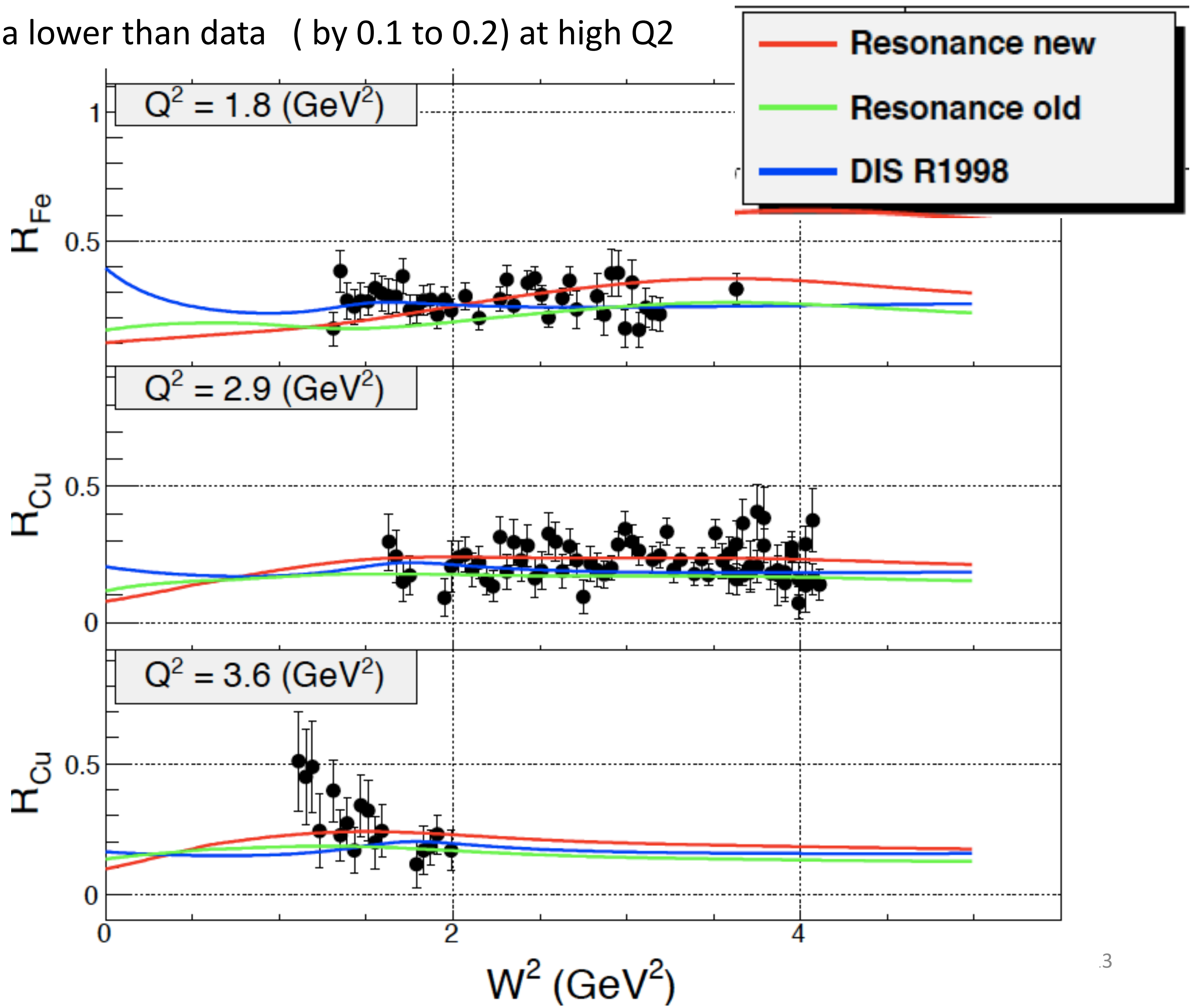
"

Measurements of the Transverse and Longitudinal Structure Functions in Electron Scattering on Nuclear Targets

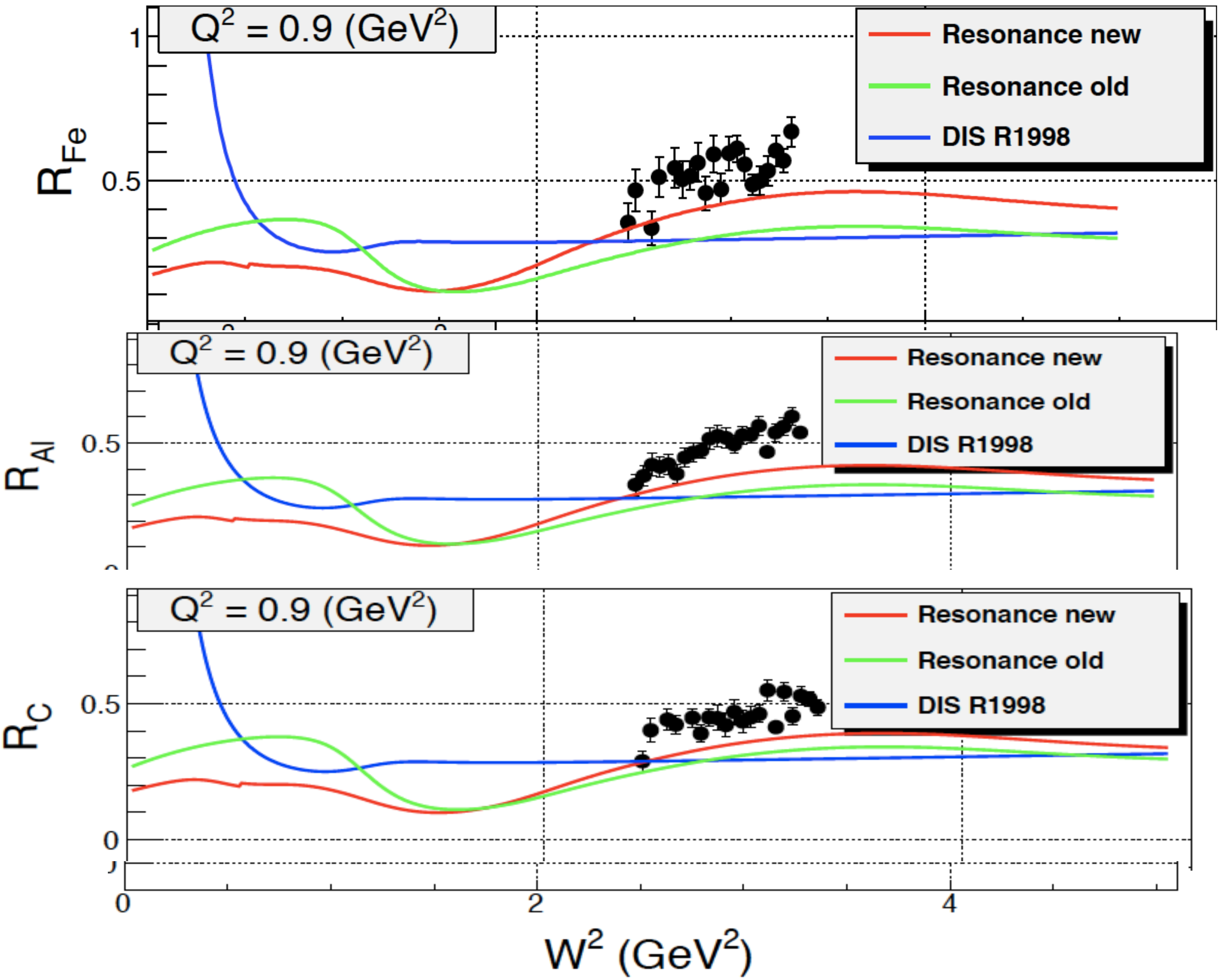
V. Mamyan,[27] A. Ahmidouch,[22] I. Albayrak,[11] J. Arrington,[1] A. Asaturyan,[31] A. Bodek,[24] P. Bosted,[29] R. Bradford,[24,1] E. Brash,[3] A. Bruell,[5] C Butuceanu,[23] M. E. Christy,[11] S. J. Coleman,[29] M. Commisso,[27] S. Connell,[9] M. M. Dalton,[27] S. Danagoulian,[22] A. Daniel,[12] D. Day,[27] S. Dhamija,[7] J. Dunne,[18] D. Dutta,[18] R. Ent,[8] D. Gaskell,[8] A. Gasparian,[22] R. Gran,[17] T. Horn,[8] Liting Huang,[11] G. M. Huber,[23] C. Jayalath,[11] M. Johnson,[1,21] M. Jones,[8] N. Kalantarians,[12] A. Liyanage,[11] C. Keppel,[11] E. Kinney,[4] Y. Li,[11] S. Malace,[6] S. Manly,[24] P. Markowitz,[7] J. Maxwell,[27] N. N. Mbianda,[9] K. S. McFarland,[24] M. Meziane,[29] Z. E. Meziani,,[26] G. B Mills,[15] H. Mkrtchyan,[31] A. Mkrtchyan,[31] J. Mulholland,[27] J. Nelson,[29] G. Niculescu,[10] I. Niculescu,[10] L. Pentchev,[29] A. Puckett,[16,15] V. Punjabi,[20] I. A. Qattan,[13] P. E. Reimer,[1] J. Reinhold,[7] V. M Rodriguez,[12] O. Rondon-Aramayo,[27] M. Sakuda,[14] W. K. Sakumoto,[24] E. Segbefia,[11] T. Seva,[32] I. Sick,[2] K. Slifer,[19] G. R, Smith,[8] J. Steinman,[24] P. Solvignon,[1] V. Tadevosyan,[31] S. Tajima,[27] V. Tvaskis,[30] G. R. Smith,[8] W. Vulcan,[8] T. Walton,[11] F. R Wesselmann,[20] S. A. Wood,[8] and Zhihong Ye[11]

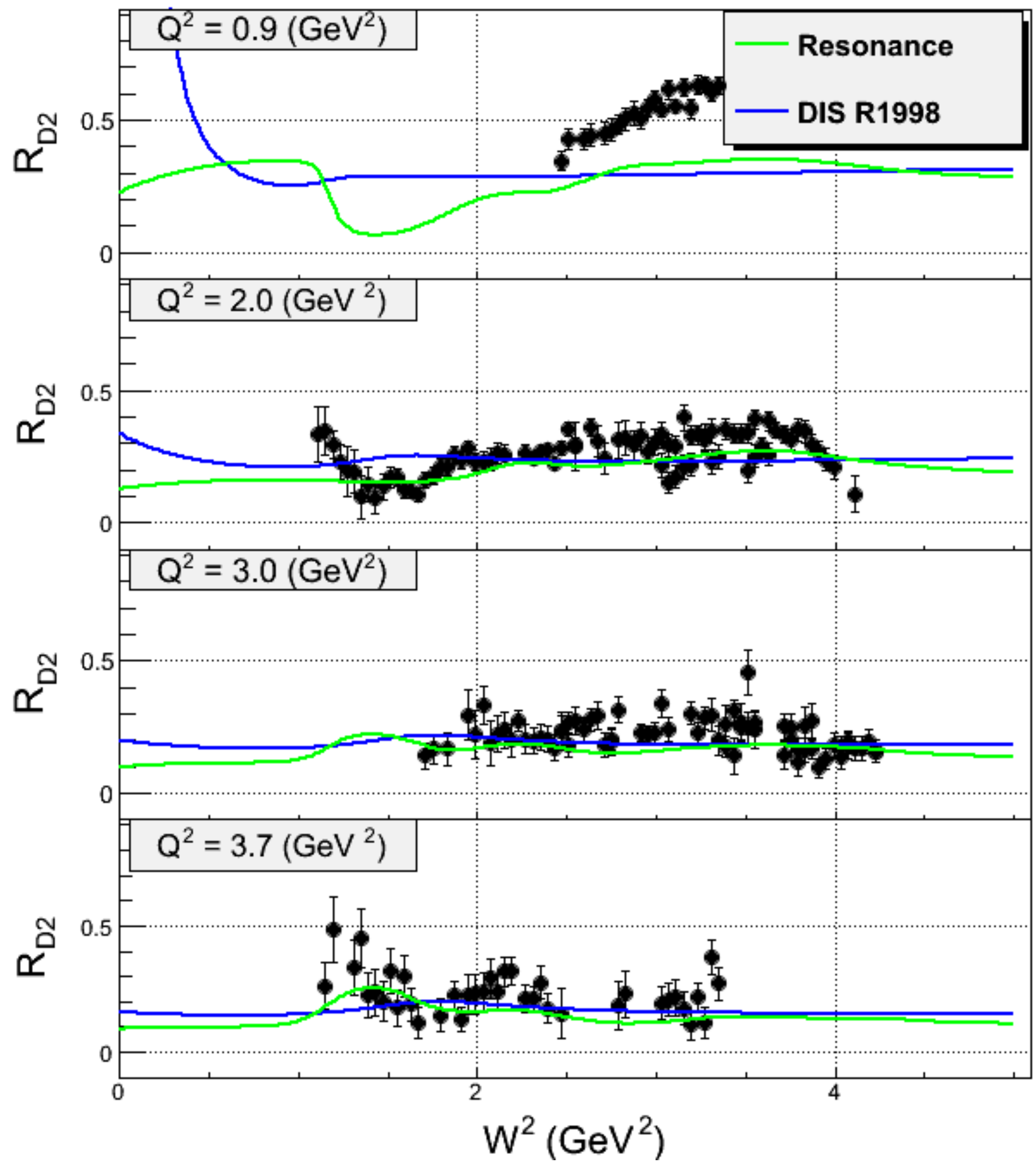
(The JUPITER Collaboration Jlab E02-109, E04-001, E06-009)

R1998 is a lower than data   (by 0.1 to 0.2) at high Q2



Most of cross section is at small Q2, R1998 is too small here also (0.1 to 0.3)





R for deuterium

How R_A vs R_D

For W2 > 2 GeV2

R_Cu - R_D = -0.066+-0.007

R_C - R_D = -0.047+-0.006

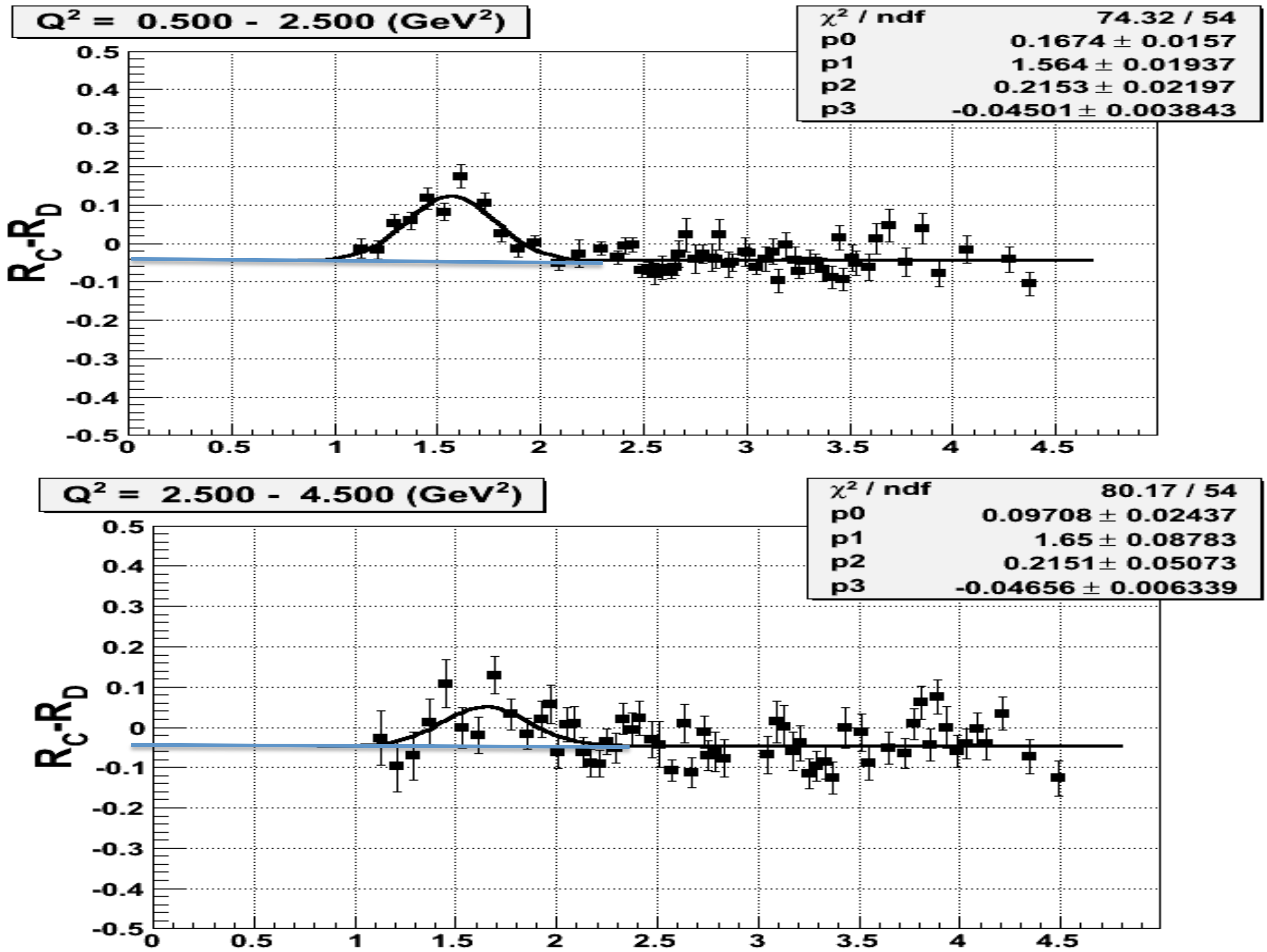
R_Cu - R_C = -0.020+-0.007

So R_D is even higher than R_Cu

Means F2A/F2D is not equal to F1A/F1D.

F1Cu/F1Cu = F2Cu/F2Cu * (1-0.066)

Extractions of EMC ratio assumed that RA=RD. These results need to be updated
When final RA-RD results are published.

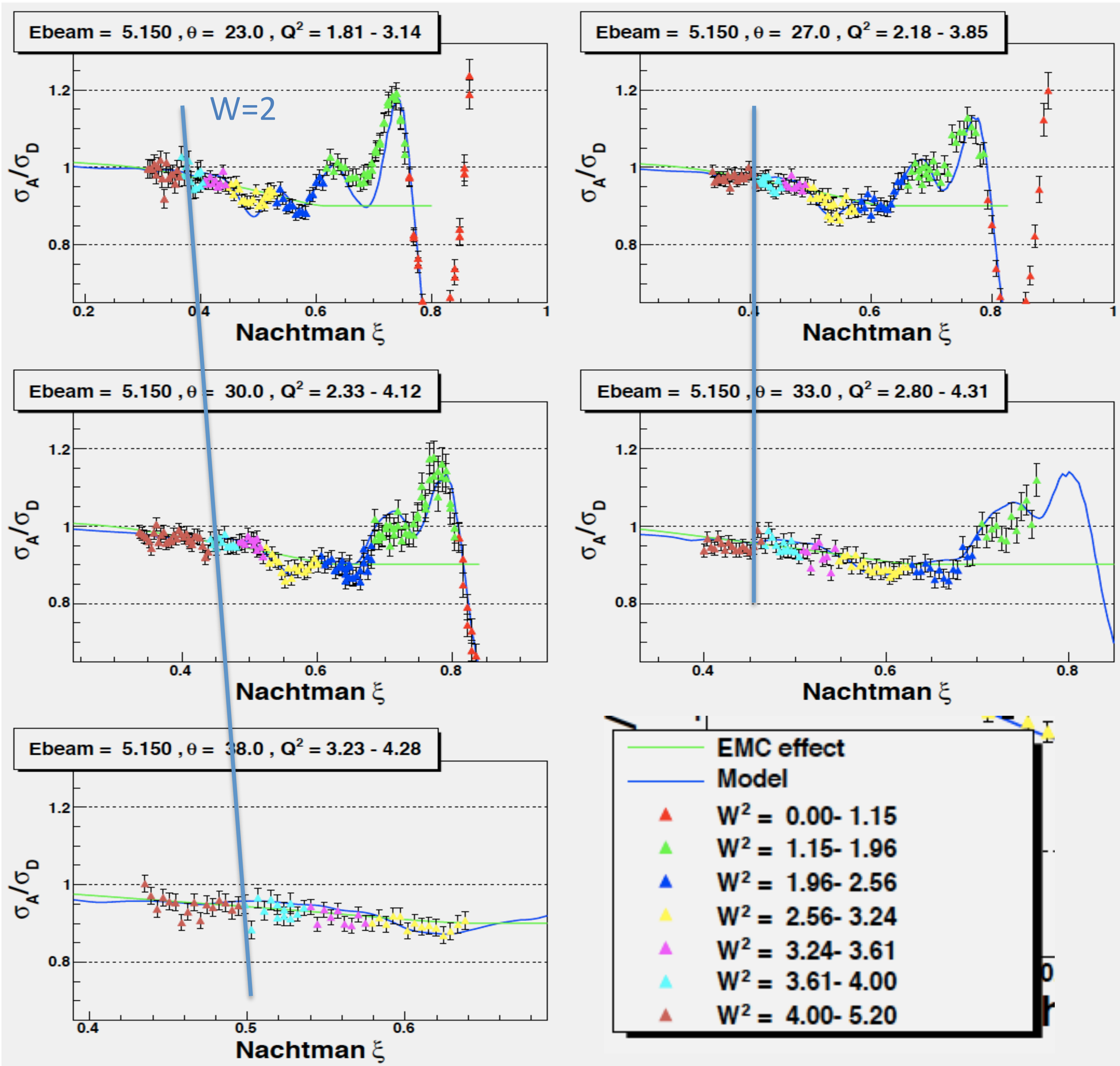

Q² = 0.500 - 2.500 (GeV²)
χ² / ndf 74.32 / 54
p0 0.1674 ± 0.0157
p1 1.564 ± 0.01937
p2 0.2153 ± 0.02197
p3 -0.04501 ± 0.003843
R_C-R_D
Q² = 2.500 - 4.500 (GeV²)
χ² / ndf 80.17 / 54
p0 0.09708 ± 0.02437
p1 1.65 ± 0.08783
p2 0.2151 ± 0.05073
p3 -0.04656 ± 0.006339
R_C-R_D

What's next about R

- Complete the analysis of lower Q2 data (which is of more of interest to neutrino experiments)
- Extract fits to R for H, D and nuclear targets that extend down below Q2=0.9 for use by the neutrino community and for re-analysis of EMC data on the EMC effect/nuclear shadowing.
- Need to parametrize EMC effect in Resonance region and structure function in resonance region. (see next slides)

Next slide Studies of EMC effect/shadowing

Structure functions in Resonance Region on nuclear targets

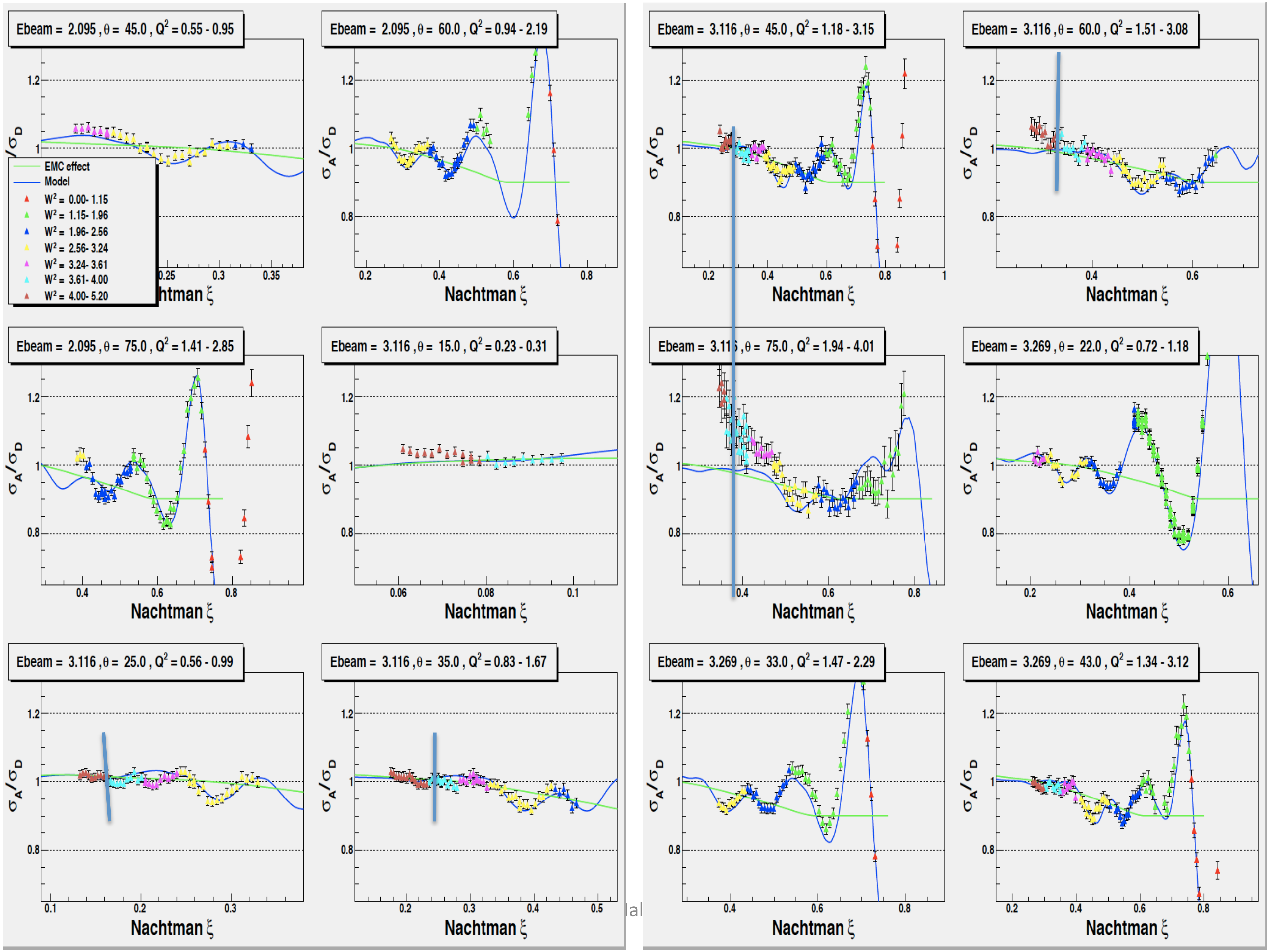


Studies on ratio F2A/F2D in resonance region are important.

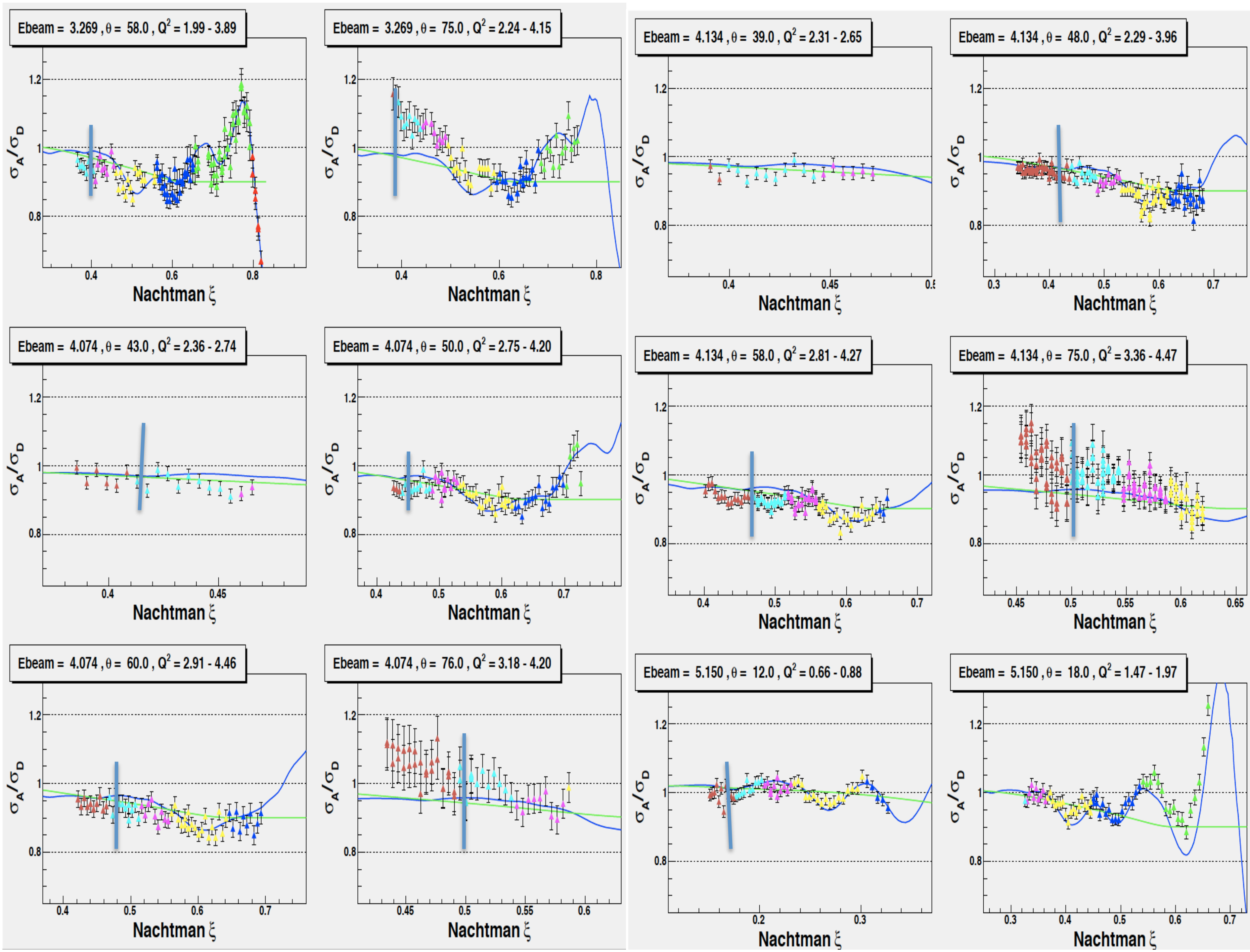
Does ratio follow DIS curve in Xsi , or X (averaged over mass of resonance).

What happens in the region of the Delta?

What happens in the QE region?


Ebeam = 2.095 , θ = 45.0 , Q² = 0.55 - 0.95
Ebeam = 2.095 , θ = 60.0 , Q² = 0.94 - 2.19
Ebeam = 3.116 , θ = 45.0 , Q² = 1.18 - 3.15
Ebeam = 3.116 , θ = 60.0 , Q² = 1.51 - 3.08
Ebeam = 2.095 , θ = 75.0 , Q² = 1.41 - 2.85
Ebeam = 3.116 , θ = 15.0 , Q² = 0.23 - 0.31
Ebeam = 3.116 , θ = 75.0 , Q² = 1.94 - 4.01
Ebeam = 3.269 , θ = 22.0 , Q² = 0.72 - 1.18
Ebeam = 3.116 , θ = 25.0 , Q² = 0.56 - 0.99
Ebeam = 3.116 , θ = 35.0 , Q² = 0.83 - 1.67
Ebeam = 3.269 , θ = 33.0 , Q² = 1.47 - 2.29
Ebeam = 3.269 , θ = 43.0 , Q² = 1.34 - 3.12
EMC effect
Model
W² = 0.00- 1.15
W² = 1.15- 1.96
W² = 1.96- 2.56
W² = 2.56- 3.24
W² = 3.24- 3.61
W² = 3.61- 4.00
W² = 4.00- 5.20
σA/σD
Nachtman ξ

al



Ebeam = 3.269 , θ = 58.0 , Q² = 1.99 - 3.89
Ebeam = 3.269 , θ = 75.0 , Q² = 2.24 - 4.15
Ebeam = 4.134 , θ = 39.0 , Q² = 2.31 - 2.65
Ebeam = 4.134 , θ = 48.0 , Q² = 2.29 - 3.96
Ebeam = 4.074 , θ = 43.0 , Q² = 2.36 - 2.74
Ebeam = 4.074 , θ = 50.0 , Q² = 2.75 - 4.20
Ebeam = 4.134 , θ = 58.0 , Q² = 2.81 - 4.27
Ebeam = 4.134 , θ = 75.0 , Q² = 3.36 - 4.47
Ebeam = 4.074 , θ = 60.0 , Q² = 2.91 - 4.46
Ebeam = 4.074 , θ = 76.0 , Q² = 3.18 - 4.20
Ebeam = 5.150 , θ = 12.0 , Q² = 0.66 - 0.88
Ebeam = 5.150 , θ = 18.0 , Q² = 1.47 - 1.97
σA/σD
Nachtman ξ

Quasielastic Scattering Requires more study for neutrino experiments – Electron scattering provides important information

Neutrino Quasielastic Scattering on Nuclear Targets

Resolving the axial mass anomaly

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

Arie Bodek and Howard Budd

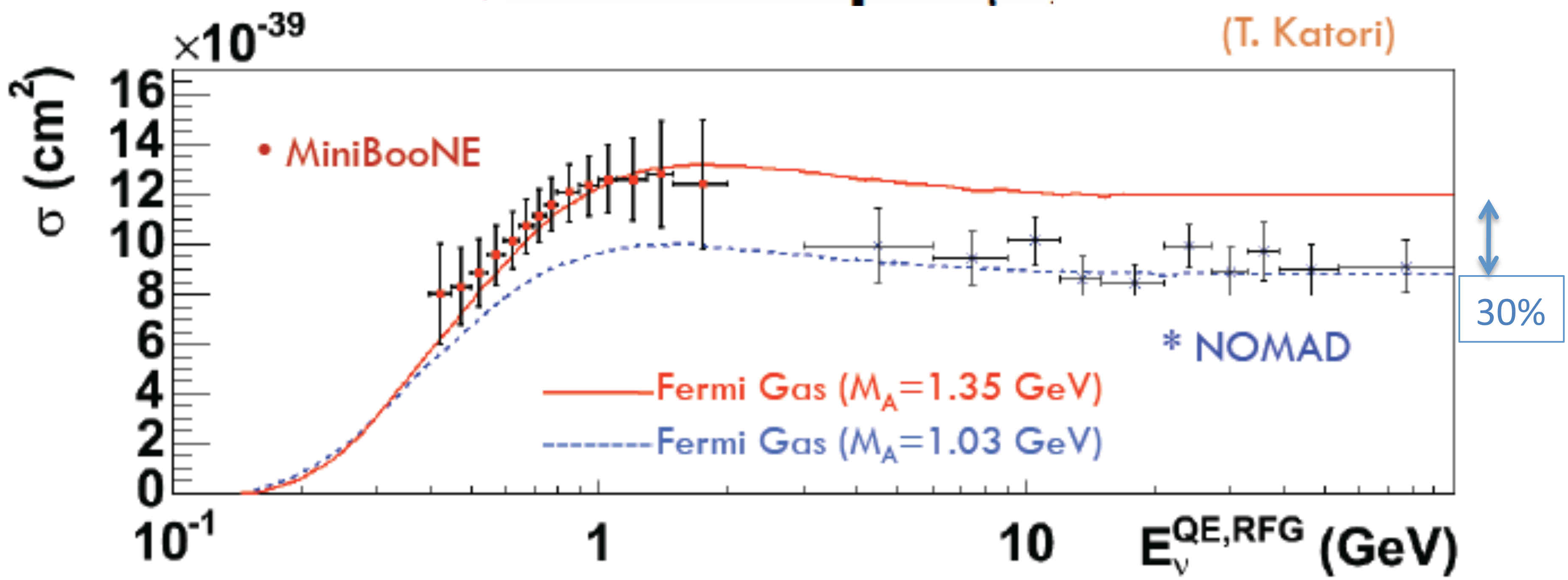
University of Rochester

M. Eric Christy

Hampton University

QE Cross Section on ^{12}C

Axial Mass anomaly: $\nu + n \rightarrow p + \mu^-$



Total QE cross sections at low and high energy inconsistent

Low energy cross sections on nuclear targets are 20% high, consistent with: M_A=1.35

CURVES: INDEPENDENT NUCLEON MODEL

High energy experiments on nuclear targets are consistent with : M_A=1.03 (= free nucleon value) → difference in high energy cross section is 30%.

What do we learn from electron scattering data on nuclear targets.

T. W. Donnelly and I. Sick, Phys. Rev. C60, 065502 (1999)

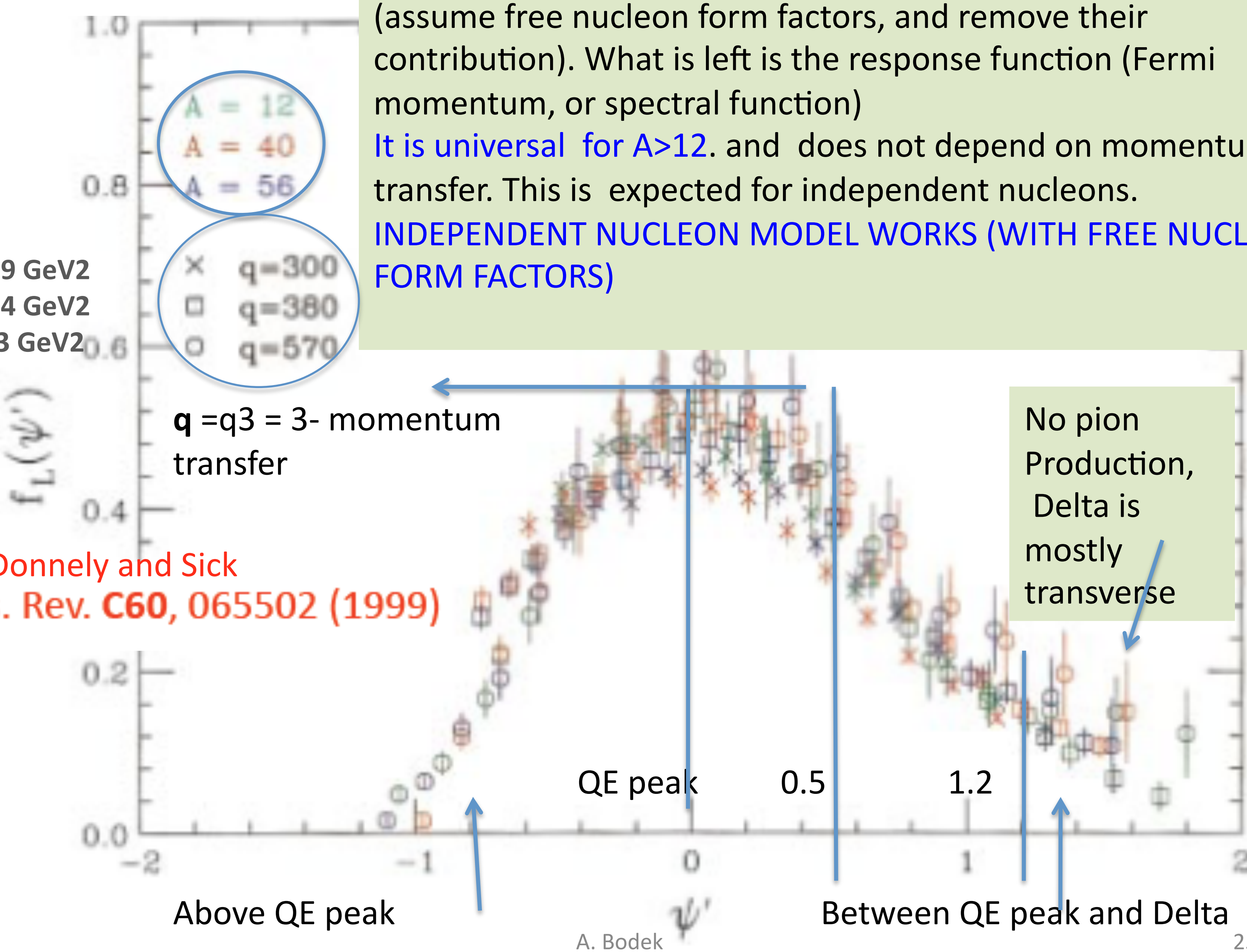
1. Model of Independent nucleon with Fermi motion and *free nucleon form factors* works for the longitudinal part of the QE cross sections

2. The transverse part of the QE cross sections shows an excess which is Q^2 dependent

3. This was known for over a decade.

Electron QE scattering: Longitudinal Response Function

Longitudinal response function in QE electron scattering (assume free nucleon form factors, and remove their contribution). What is left is the response function (Fermi momentum, or spectral function)
It is universal for A>12. and does not depend on momentum transfer. This is expected for independent nucleons.
INDEPENDENT NUCLEON MODEL WORKS (WITH FREE NUCLEON FORM FACTORS)



Q^2 =0.09 GeV2
Q^2=0.14 GeV2
Q^2- 0.33 GeV2

q =q3 = 3- momentum transfer

No pion Production, Delta is mostly transverse

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

QE peak 0.5 1.2

Above QE peak

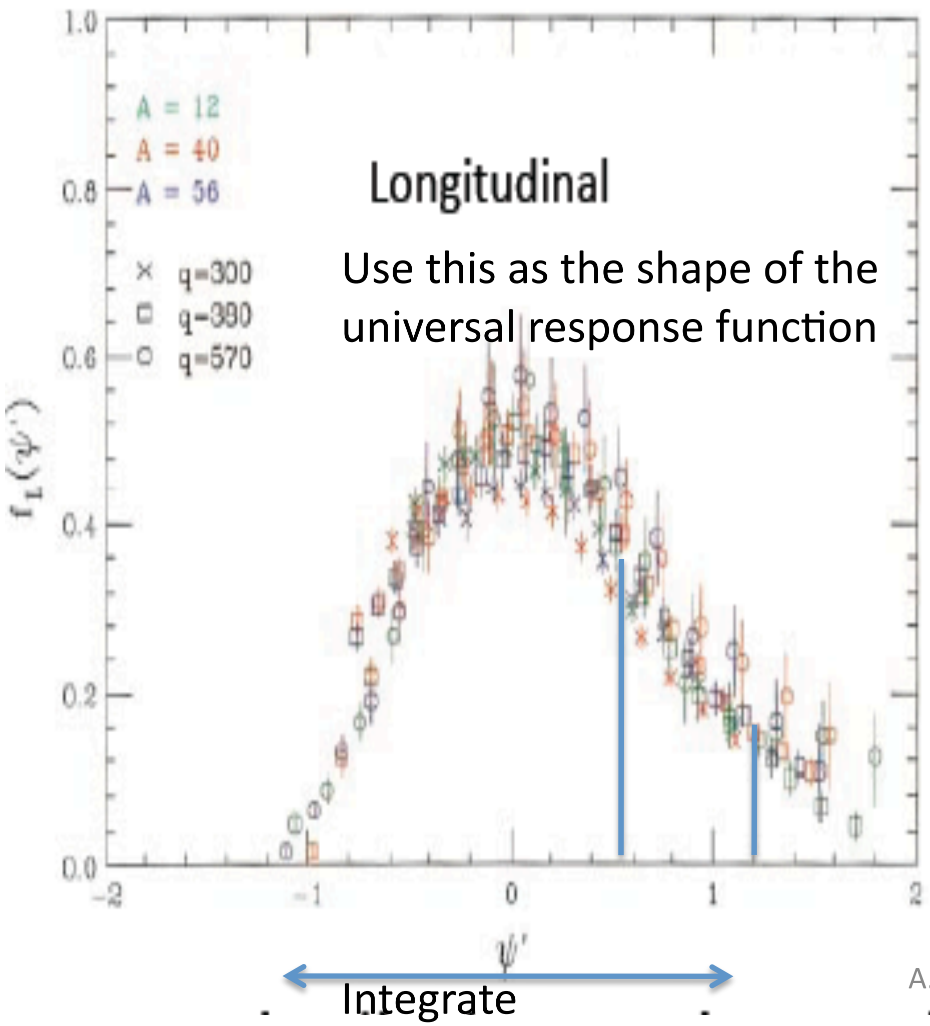
Between QE peak and Delta

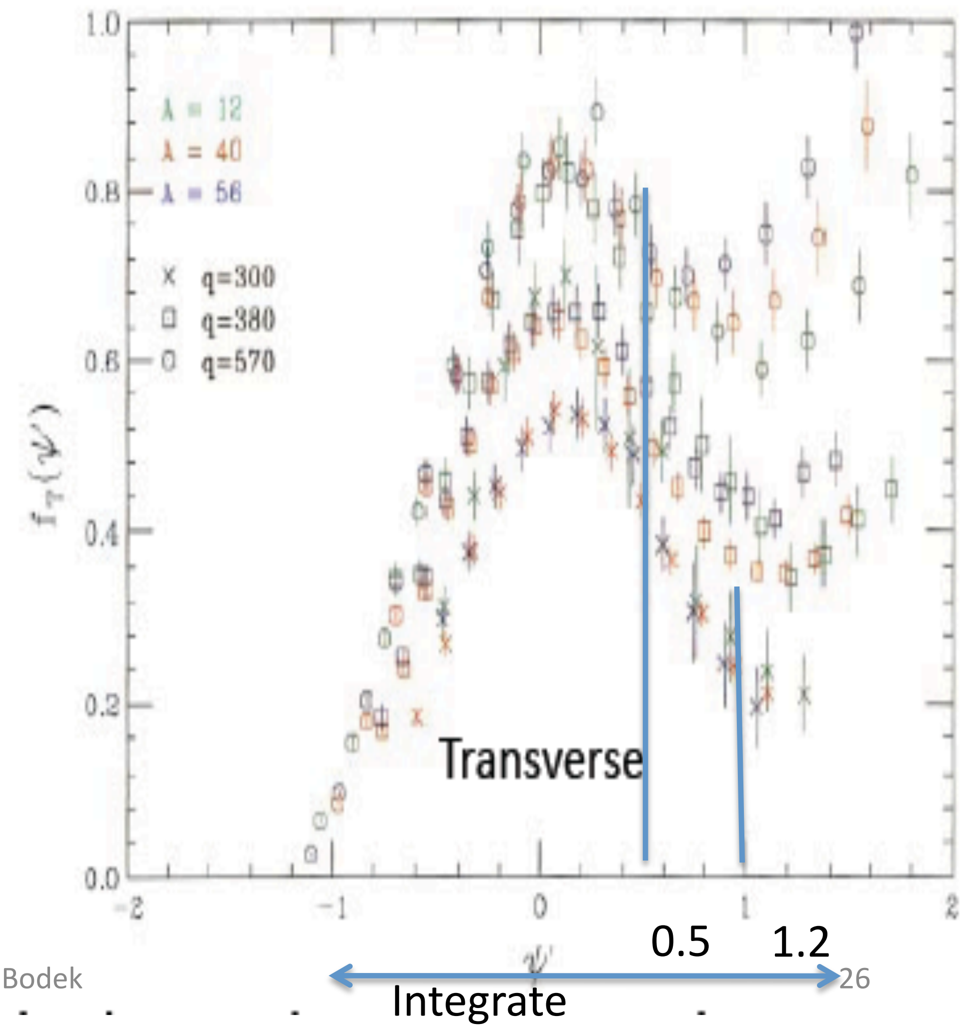
Donnely and Sick Phys. Rev. **C60**, 065502 (1999)

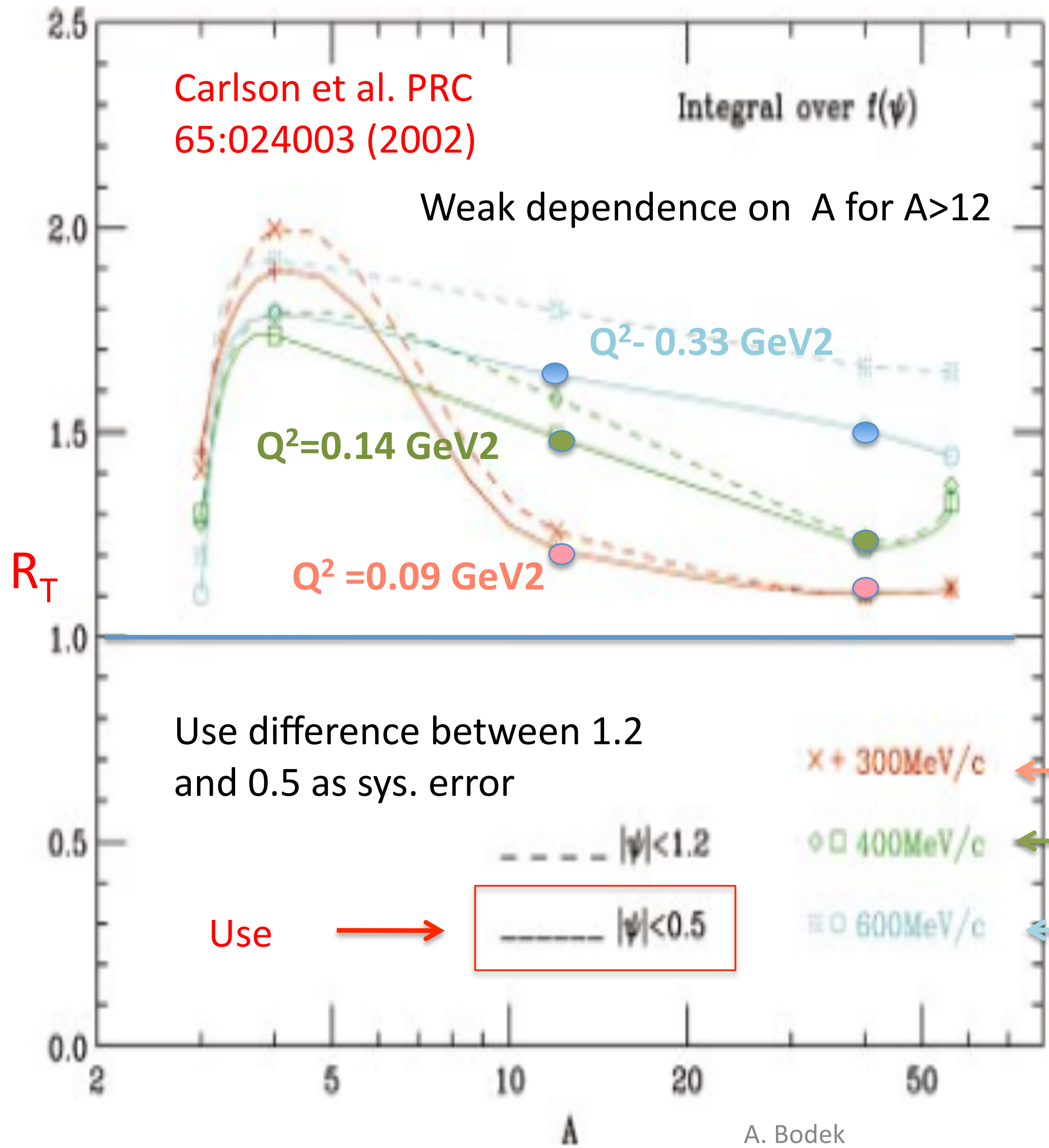
Response functions (assume free nucleon form factors, and remove their Q2 dependence)

Longitudinal agrees with the independent nucleon model

Transverse is enhanced by a Q^2 dependent factor R_T







R_T= Ratio of Integrated Transverse to Longitudinal response functions (same as ratio of transverse to independent nucleons).

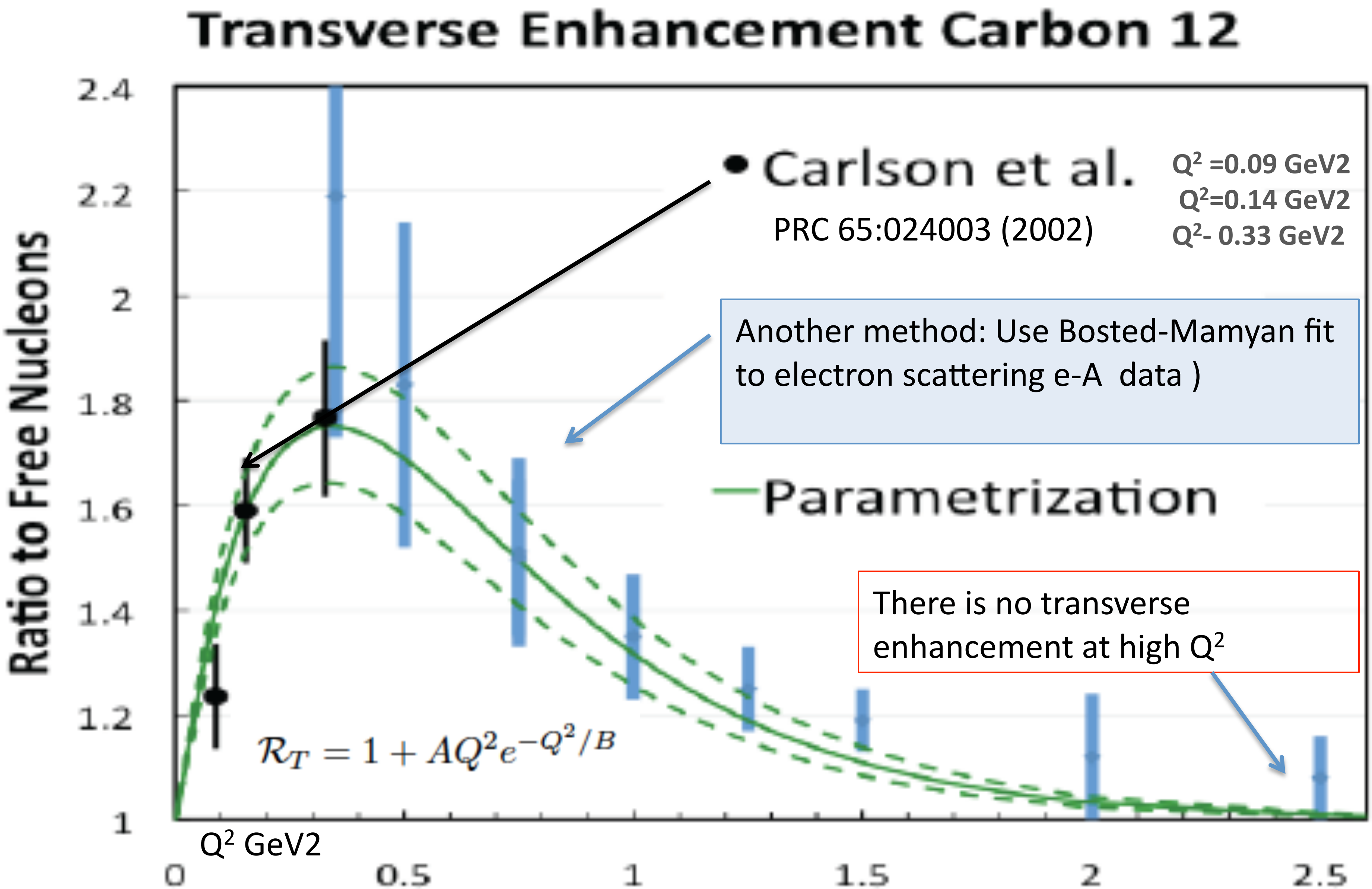
Carslon et al. extracted R_T for Carbon and Calcium at:

Q^2 =0.09 GeV2

Q^2=0.14 GeV2

Q^2- 0.33 GeV2

To get R_T at higher Q^2 we use another method.



Use Carlson integrated excess : Ratio R_T (ratio to universal response function)

Correct It for for high side tail

Extracting transverse enhancement at higher Q^2 ($> 0.3\ GeV^2$) from e-A data

- In electron scattering, the QE cross section is dominated by Longitudinal part at low Q^2 and Transverse part at high Q^2.

  Therefore, at low Q^2 we need to separate L and T to get the Trans. Enhancement (since the cross section is mostly longitudinal). QE and $\Delta(1232)$ production are well separated at low Q^2. Pauli blocking mostly cancels in ratio of T and L.

- At high Q^2, L is small, so it cannot be used as a normalization. Here Trans. Enhancement is the ratio of the measured cross section to the prediction of the independent nucleon model - Here we need to separate QE from $\Delta(1232)$ production (with Fermi motion). At high Q^2, Pauli blocking is negligible.

In order to do the radiative corrections to e-A data, we do a fit to *electron scattering data from many experiments over a large range of energies and Q2*.

The fit includes the following three components

$QE_{Longitudinal}$	– The longitudinal QE contribution calculated for independent nucleons (smeared by Fermi motion in carbon)	QE
$QE_{transverse}$	– The transverse QE contribution calculated for independent nucleons (smeared by Fermi motion in carbon)	QE
	– A transverse enhancement contribution	TE
	– The contribution of pion production from the Δ resonance (smeared by Fermi motion in carbon)	Inelastic
	– The contribution of higher resonances and inelastic scattering (smeared by Fermi motion in carbon)	Inelastic

calculation includes Pauli Blocking.

Fit developed by Peter Bosted and tuned by Vahe Mamyan for E04-001 It uses fits to all experimental data on H and D, (by Bosted and Christy) As input for fitting the data on nuclear targets. For QE super-scaling model of Sick, Donnelly, Maieron (nucl-th/0109032) is used.

Bosted-Mamyan fit

In order to fit the data on nuclear targets we find that a *TE component is needed*.

We take the TE component from the fit, Integrate up to $W^2 = 1.5$, and extract $R_T(Q^2) = (QE_{trans} + TE)/QE_{trans}$

Assign a conservative systematic error to R_T (since some of the transverse excess may be produced with final state pions)

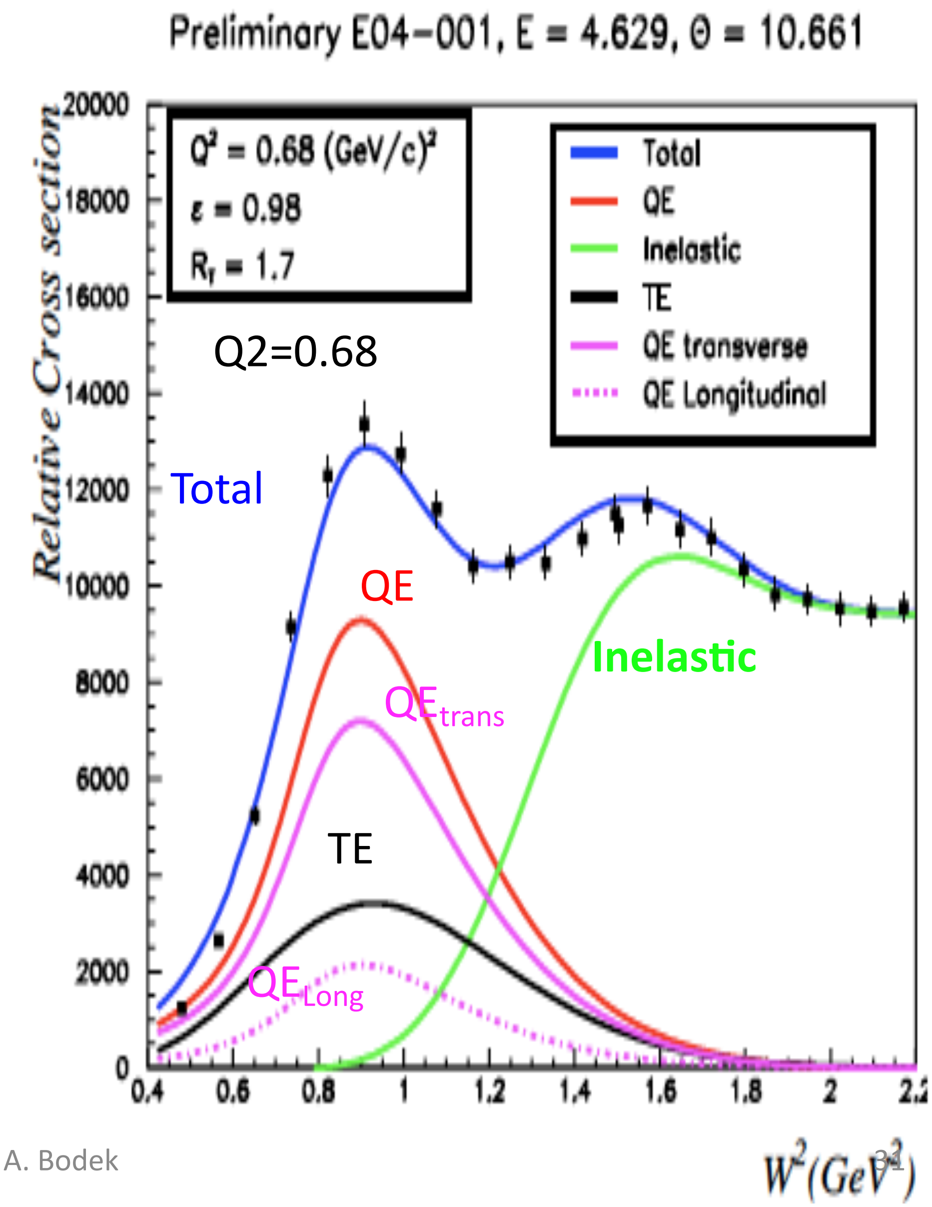
(In future we plan to improve it with updated L-T separated data from E04-001)

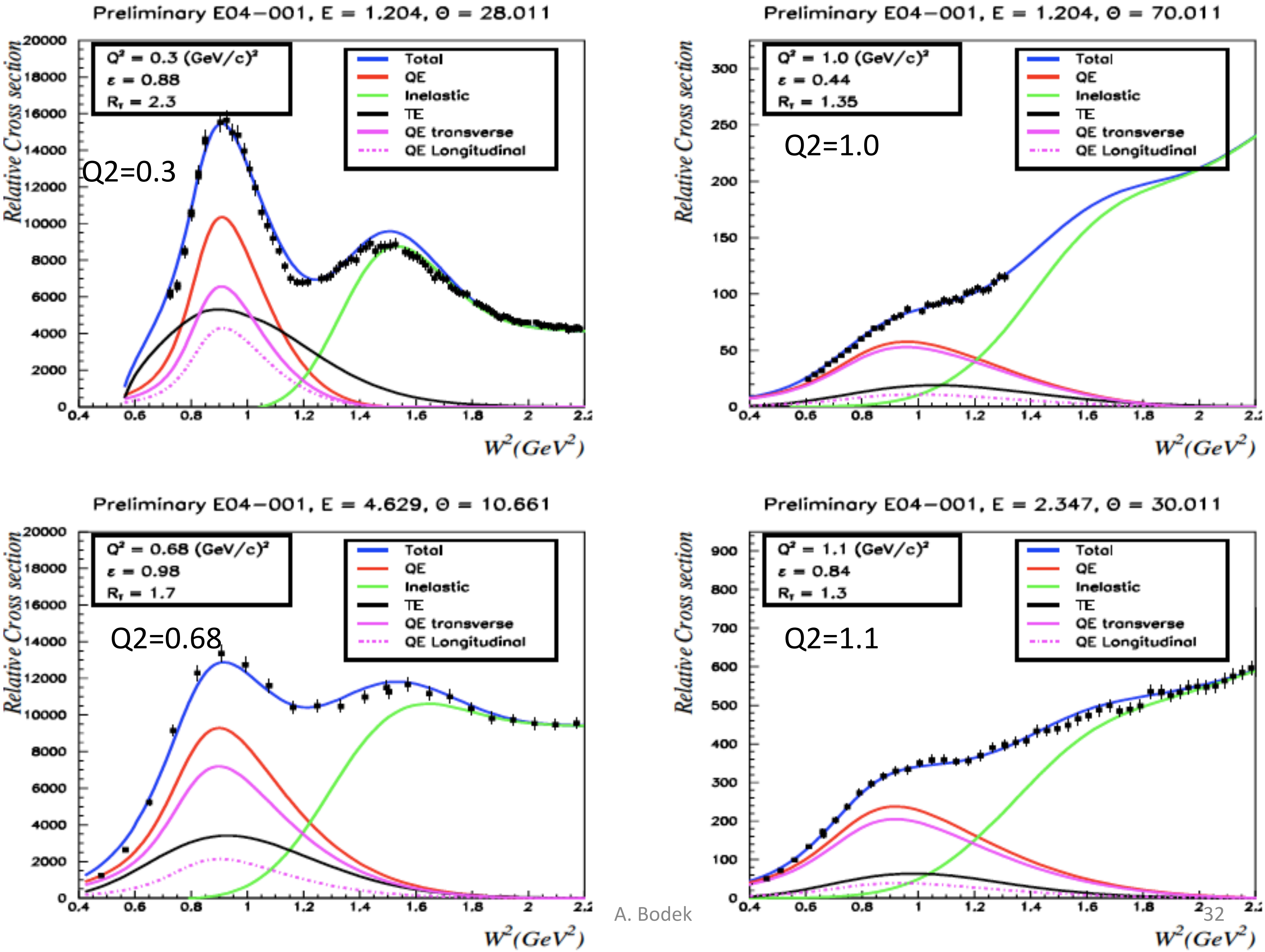
Primary purpose of this preliminary fit was as input to radiative corrections.

A spinoff of the fit is the TE component versus Q2

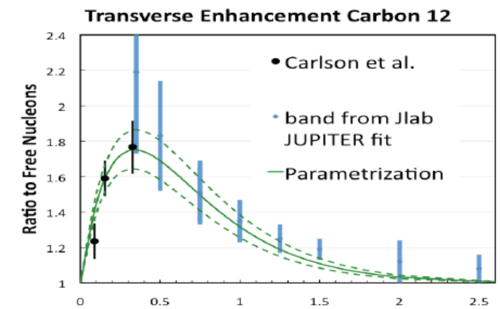
Extracting Transverse enhancement at Q^2>0.3 GeV2

$$\mathcal{R}_T = \frac{QE_{transverse} + TE}{QE_{transverse}}$$




Preliminary E04−001, E = 1.204, Θ = 28.011
Q² = 0.3 (GeV/c)²
ε = 0.88
Rᵀ = 2.3
Q2=0.3
Total
QE
Inelastic
TE
QE transverse
QE Longitudinal
Relative Cross section
W²(GeV²)
Preliminary E04−001, E = 1.204, Θ = 70.011
Q² = 1.0 (GeV/c)²
ε = 0.44
Rᵀ = 1.35
Q2=1.0
Preliminary E04−001, E = 4.629, Θ = 10.661
Q² = 0.68 (GeV/c)²
ε = 0.98
Rᵀ = 1.7
Q2=0.68
Preliminary E04−001, E = 2.347, Θ = 30.011
Q² = 1.1 (GeV/c)²
ε = 0.84
Rᵀ = 1.3
Q2=1.1

Transverse Enhancement has been attributed to Meson Exchange Currents



- MEC enhance only the transverse part of the QE cross section.
- MEC do not enhance the longitudinal part, or the axial part.
- By Conserved Vector Current (CVC), the transverse enhancement observed in electron scattering experiments should be seen in neutrino scattering.
- THEREFORE: We parametrize the observed transverse enhancement in electron scattering as an enhancement in the magnetic form factors GMp and GMn for bound nucleons (magnetic scattering is transverse). (This is simple to implement in current neutrino MCs)
- And predict neutrino QE diff and total cross sections using the independent nucleon model with free nucleon form factors (except for Gmp and Gmn which are enhanced).

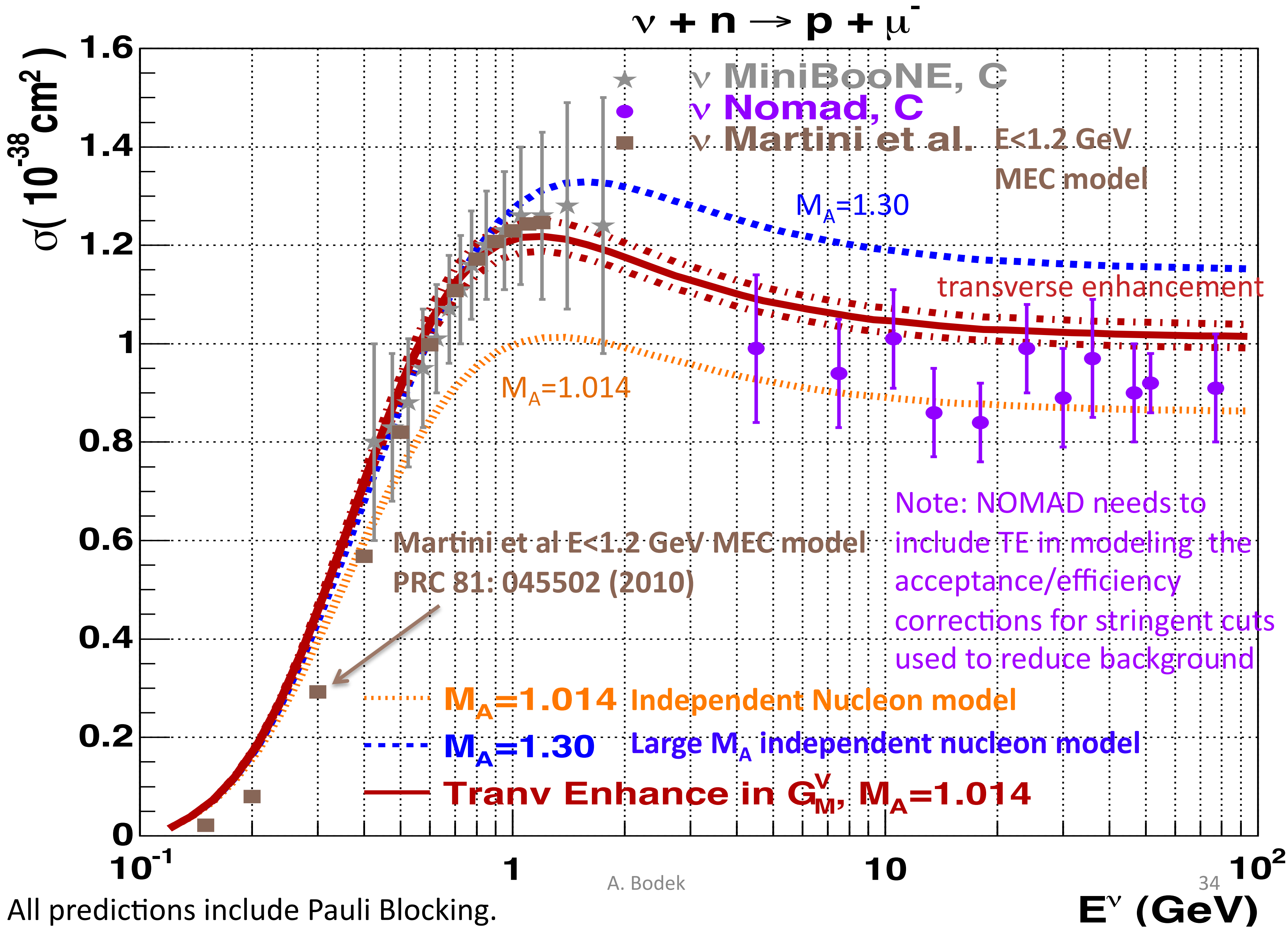
$$G_{Mp}^{nuclear}(Q^2) = G_{Mp}(Q^2) \times \sqrt{1 + AQ^2 e^{-Q^2/B}}$$
$$G_{Mn}^{nuclear}(Q^2) = G_{Mn}(Q^2) \times \sqrt{1 + AQ^2 e^{-Q^2/B}}.$$

$d\sigma/dQ^2, \nu + n \rightarrow p + \mu^-$,

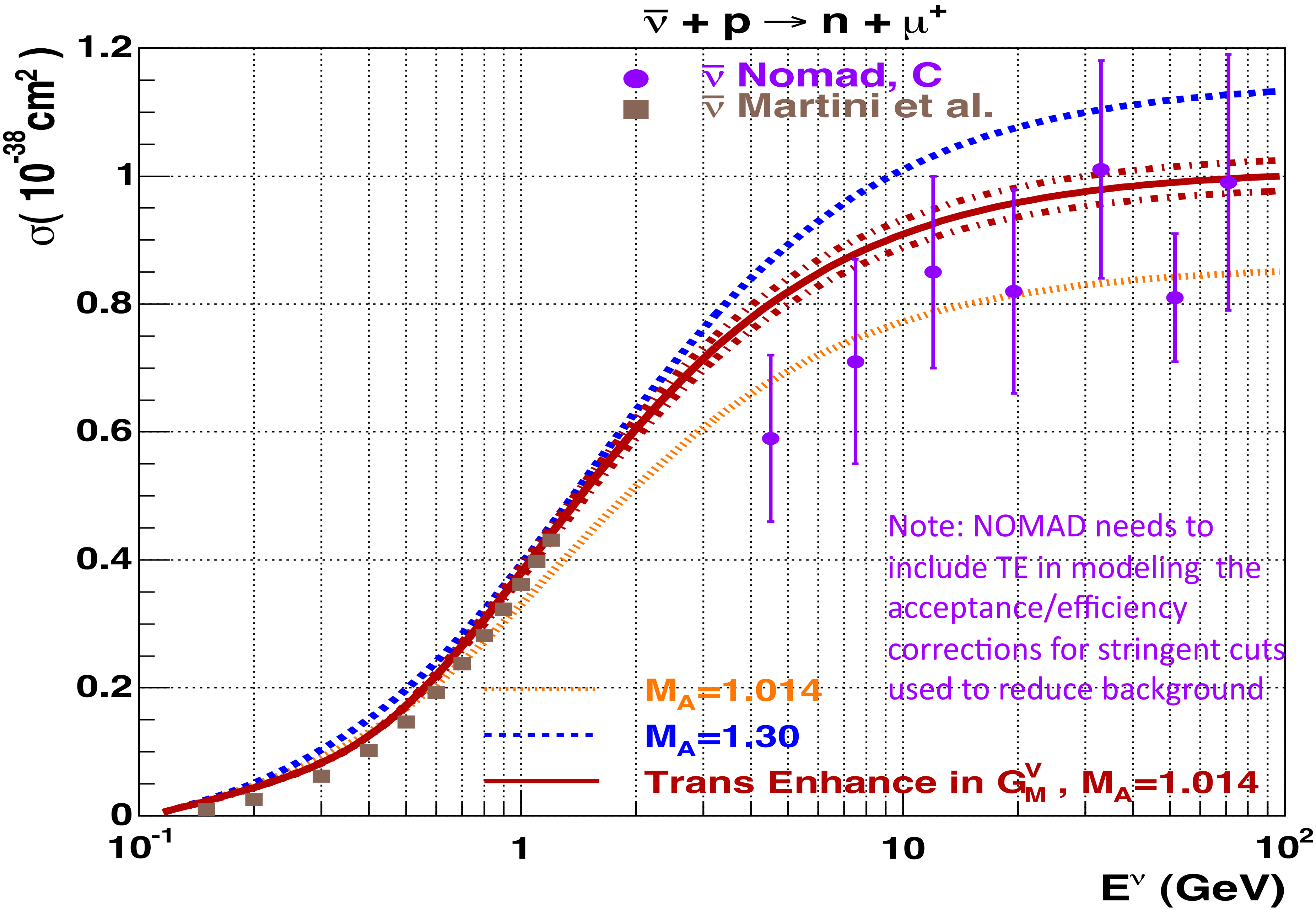
Integrated over ν

- We do not need a detailed specific model of MEC. -- Just CVC, so this is valid even if TE is not MEC (e.g. it can be any nuclear physics correction to the transverse cross section)

Total QE cross sections on Carbon (per neutron)



All predictions include Pauli Blocking.



$\bar{\nu} + p \rightarrow n + \mu^+$
$\bar{\nu}$ Nomad, C
$\bar{\nu}$ Martini et al.
Note: NOMAD needs to include TE in modeling the acceptance/efficiency corrections for stringent cuts used to reduce background
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
10^{-1}
1
10
10^2

Mores studies of QE scattering needed to improve modeling of QE in neutrino interactions

- This analysis integrates over the transverse enhancement. Which averages over ν. Therefore, it does not model the final state.
- Extraction of the TE as a function of both Q2 and ν is the next step.

QE scattering in neutrino reactions is defined as events with no final state pions.

- High momentum components with two nucleons in the final state from Short Range Correlations (SRC) are not currently modeled.
- Final states consisting of more than one nucleon in the final state (from MEC or from SRC, or Isobar excitation) are not currently modeled.
- Multi nucleons final states from FSR are modeled, but models need to be checked against data.
- Jlab experiments which measure both cross sections and final states on nuclear targets are of interest.

Conclusions

- There is a lot of interest in the neutrino community in electron scattering results on nuclear targets.
- Results need to be presented in a simple way such that they can be incorporated into existing neutrino MCs
- The studies are basically nuclear physics studies, and therefore of interest to the nuclear physics community.