Neutrino Quasielastic Scattering on Nuclear Targets

Resolving the axial mass anomaly

arXiv:1106.0340 [hep-ph]

Arie Bodek and Howard Budd

University of Rochester

M. Eric Christy

Hampton University

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Parallel 2E - Neutrino Interactions - (16:00-17:40) Room: 4-163

Problem: Q2 dependence of QE neutrino $d\sigma/dQ^2$ on nuclear targets at low and high energies are inconsistent with each other

G. Zeller 2011.

Experiment	Target	Cut in Q^2 [GeV^2]	$M_A[GeV]$
K2K[4]	oxygen	$Q^2 > 0.2$	1.2 ± 0.12
K2K[5]	carbon	$Q^2 > 0.2$	1.14 ± 0.11
MiniBooNE[7]	carbon	no cut	1.35 ± 0.17
MiniBooNE[7]	carbon	$Q^2 > 0.25$	1.27 ± 0.14

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

Low Energy neutrino experiments (< 1.5 GeV) favor M_A ~ 1.2 - 1.3 much larger than M_A for free nucleons of 1.014

Axial Mass anomaly

World average of all High Energy neutrino experiments on nuclear targets favors small M_A

0.979 ± 0.016

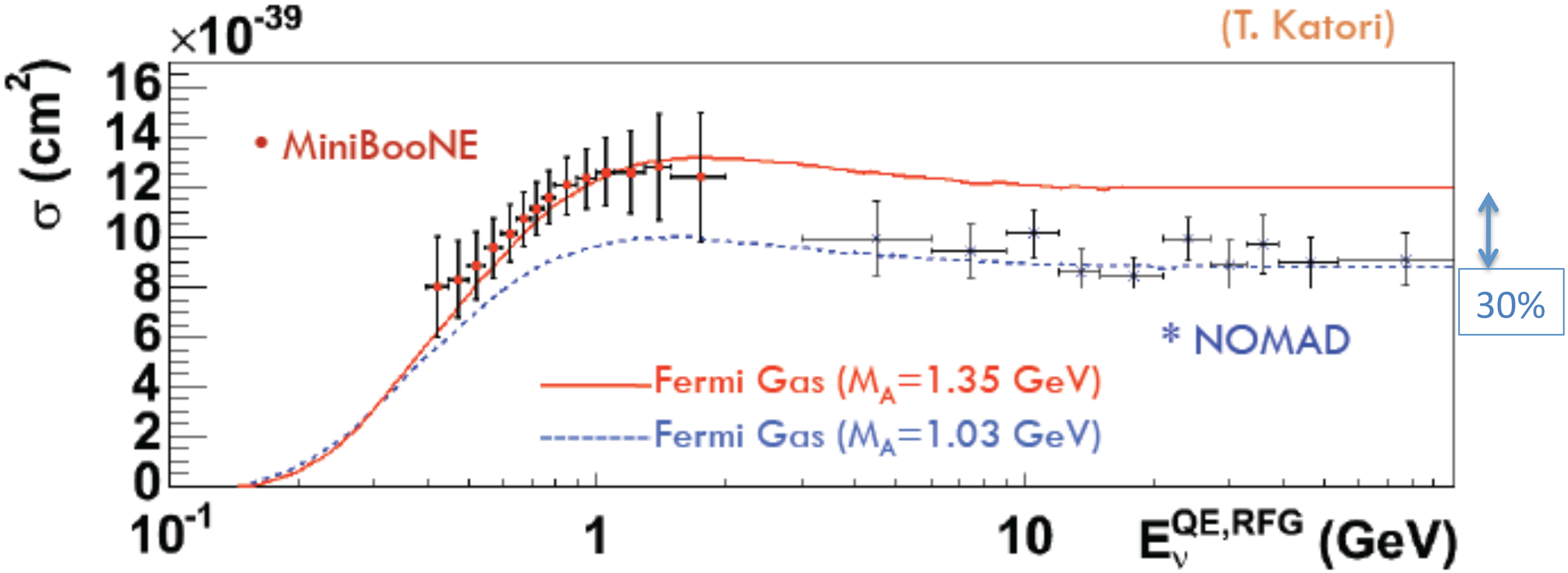
$M_A^{free} = 1.014 \pm 0.014\ GeV$

A. Bodek, S. Avvakumov, R. Bradford, and H. Budd, Eur. Phys. J. C**53**, 349 (2008).

Konstantin S. Kuzmin , Vladimir V. Lyubushkin, Vadim A. Naumov, Eur.Phys.J. C54 (2008) 517-538;

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%.

Axial Mass Anomaly

- Structure functions can depend only on Q^2 and ν
- Therefore, they must be the same at low and high energies (even for nuclear targets) – A fundamental principle of lepton scattering.
  - So which is right?
- Is it a difference in the experimental event selection process or modeling of acceptance between the low and high energy experiments of order 30% ? Or is it something new?

Note: There are theoretical arguments that the axial form factor for bound nucleons should be the same as or smaller than for free nucleons- NOT LARGER

–> large M_A in nuclei not expected theoretically.

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

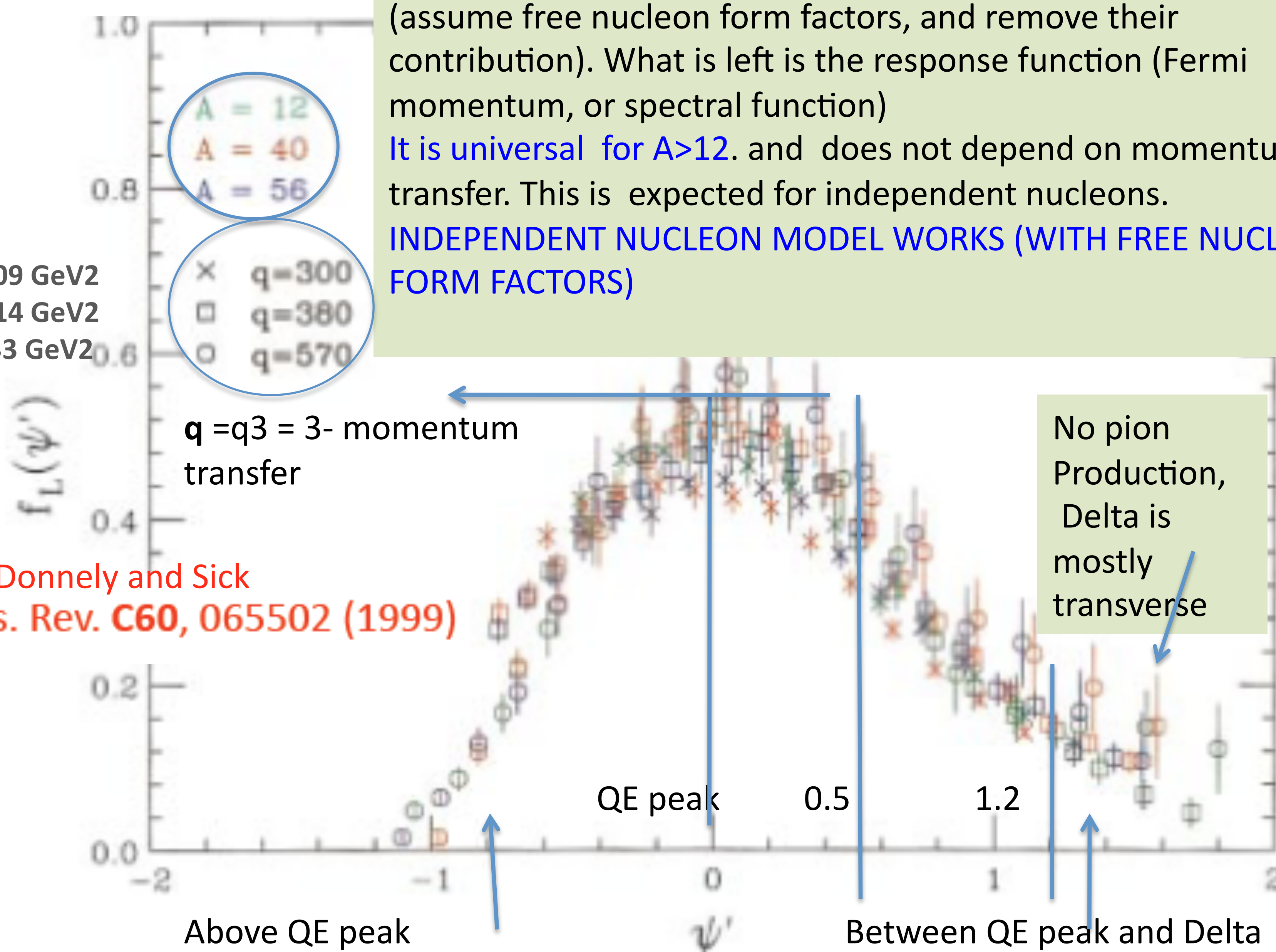
3. This was known for over a decade.

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)



Donnely and Sick

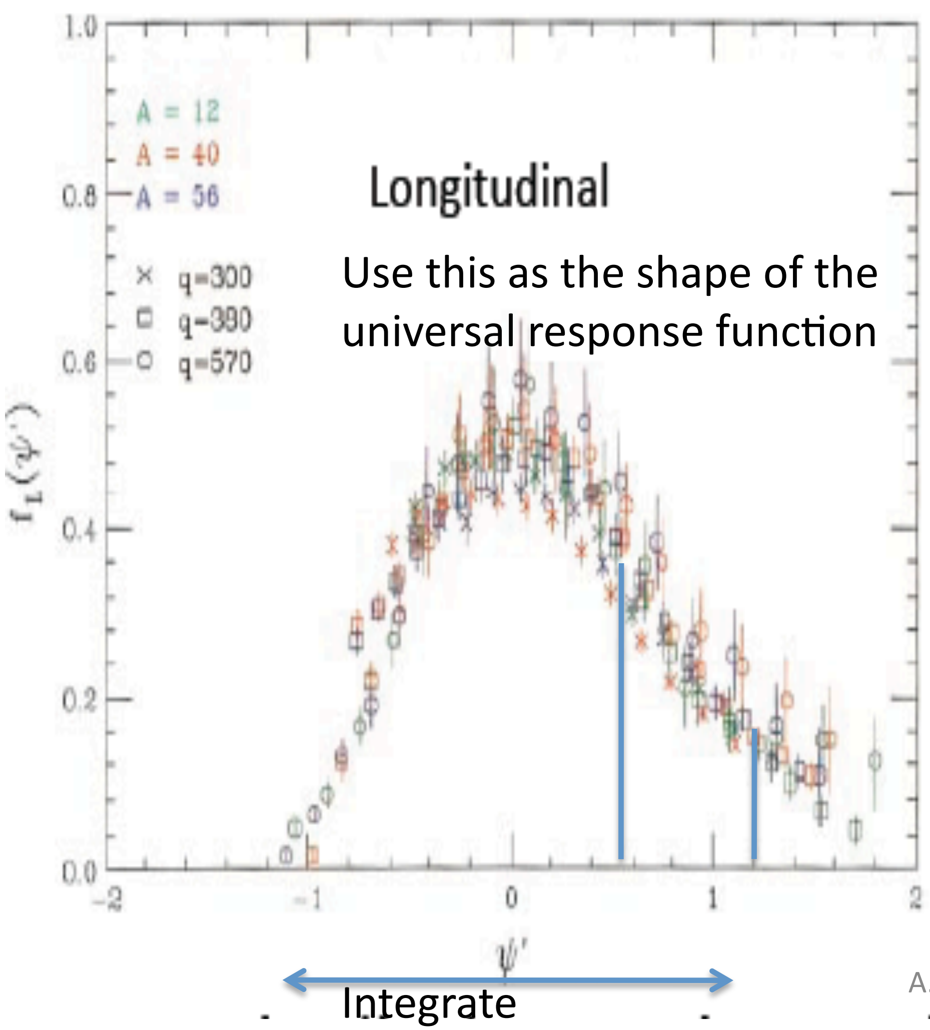
Phys. Rev. **C60**, 065502 (1999)

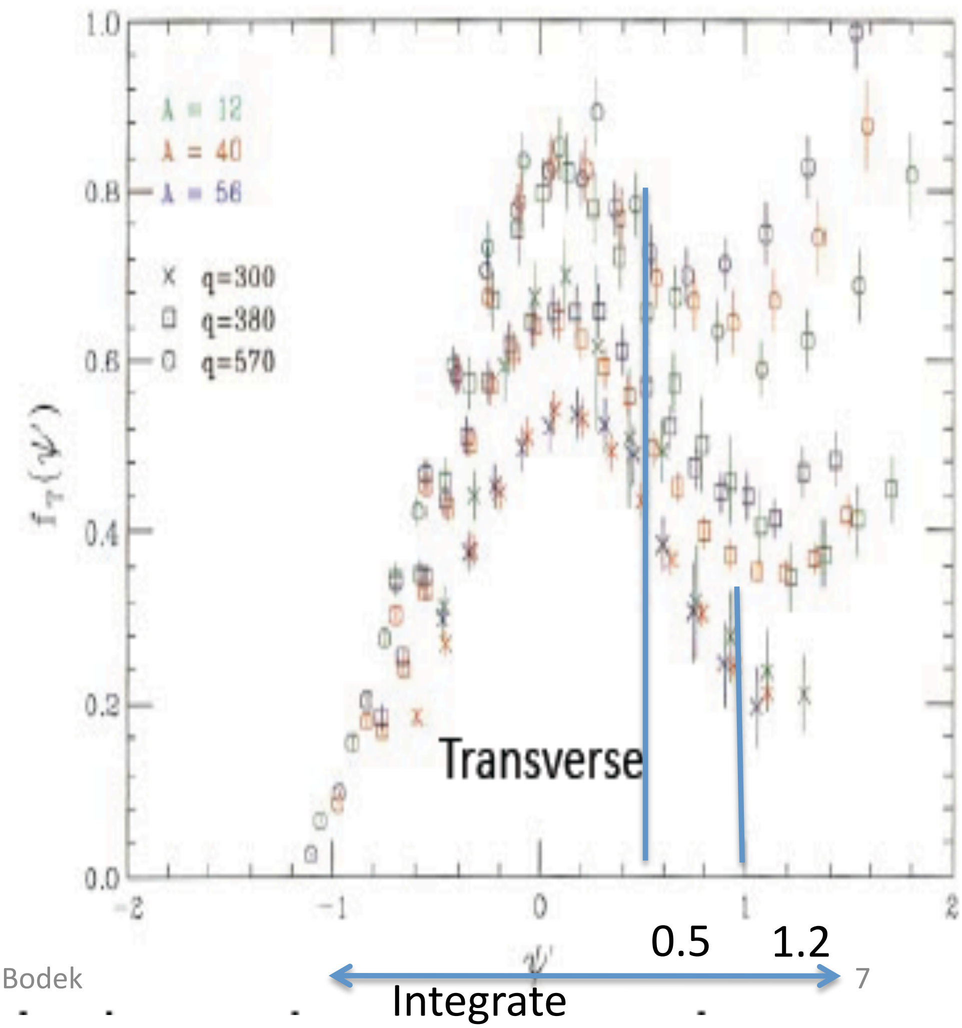
Donnely and Sick Phys. Rev. **C60**, 065502 (1999)

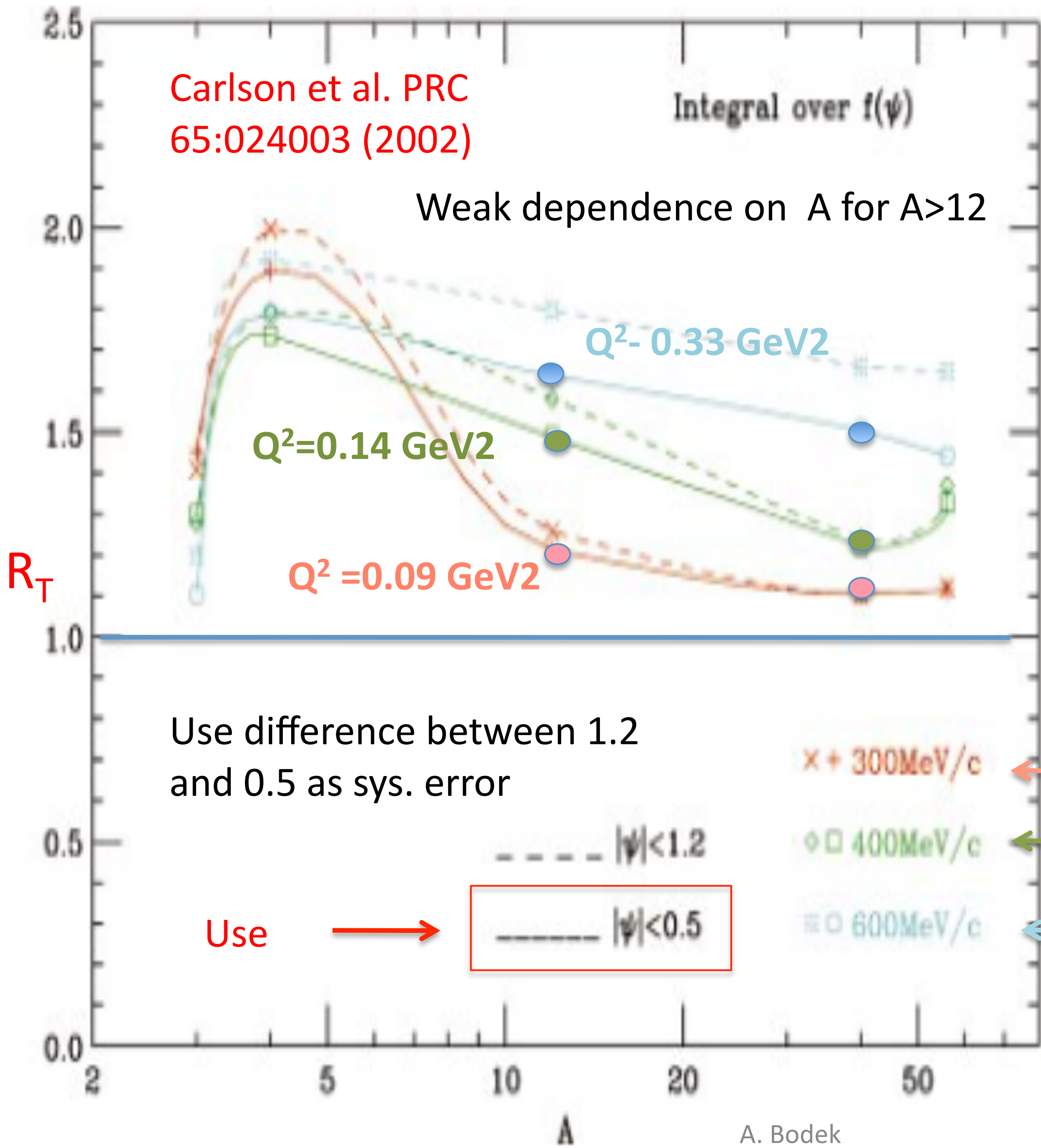
Response functions (assume free nucleon form factors, and remove their Q2 dependence)

Longitudinal agrees with the independent nucleon model

Transverse is enhanced by a Q^2 dependent factor R_T







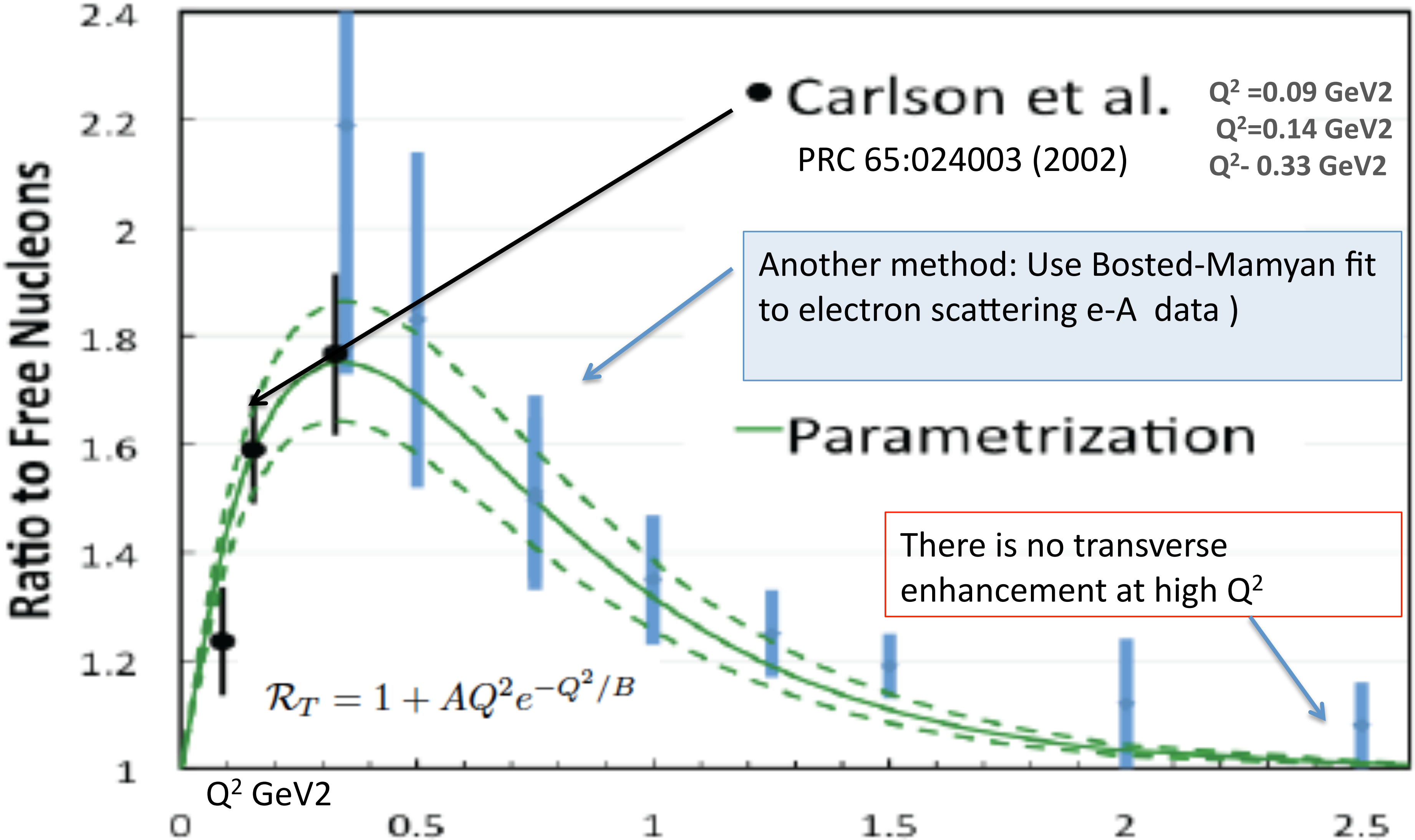
R_T= Ratio of Integrated Transverse to Longitudinal response functions (same as ratio of transverse to independent nucleons).

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.

Transverse Enhancement Carbon 12



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.

Electron scattering data on Nuclear targets

- JUPITER collaboration (E04-001) at Jlab (e-A).

Focus on investigation of electron scattering on *nuclear targets*, with emphasis on measuring L and T vector structure functions in the QE and Resonance region, for Q^2 values of interest to neutrino scattering experiments

Collaborate with Neutrino Oscillations experimenters (e.g. MINERvA, T2K).
E04-001 Spokespersons: A. Bodek, C. Keppel, M. E. Christy.

Details in:
Measurements of F2 and $R = \sigma_L/\sigma_T$ on Nuclear Targets in the Nucleon Resonance Region by Mamyan, Vahe, *Ph.D., UNIVERSITY OF VIRGINIA, 2010*

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 ***<u>TE component is needed</u>***.

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)

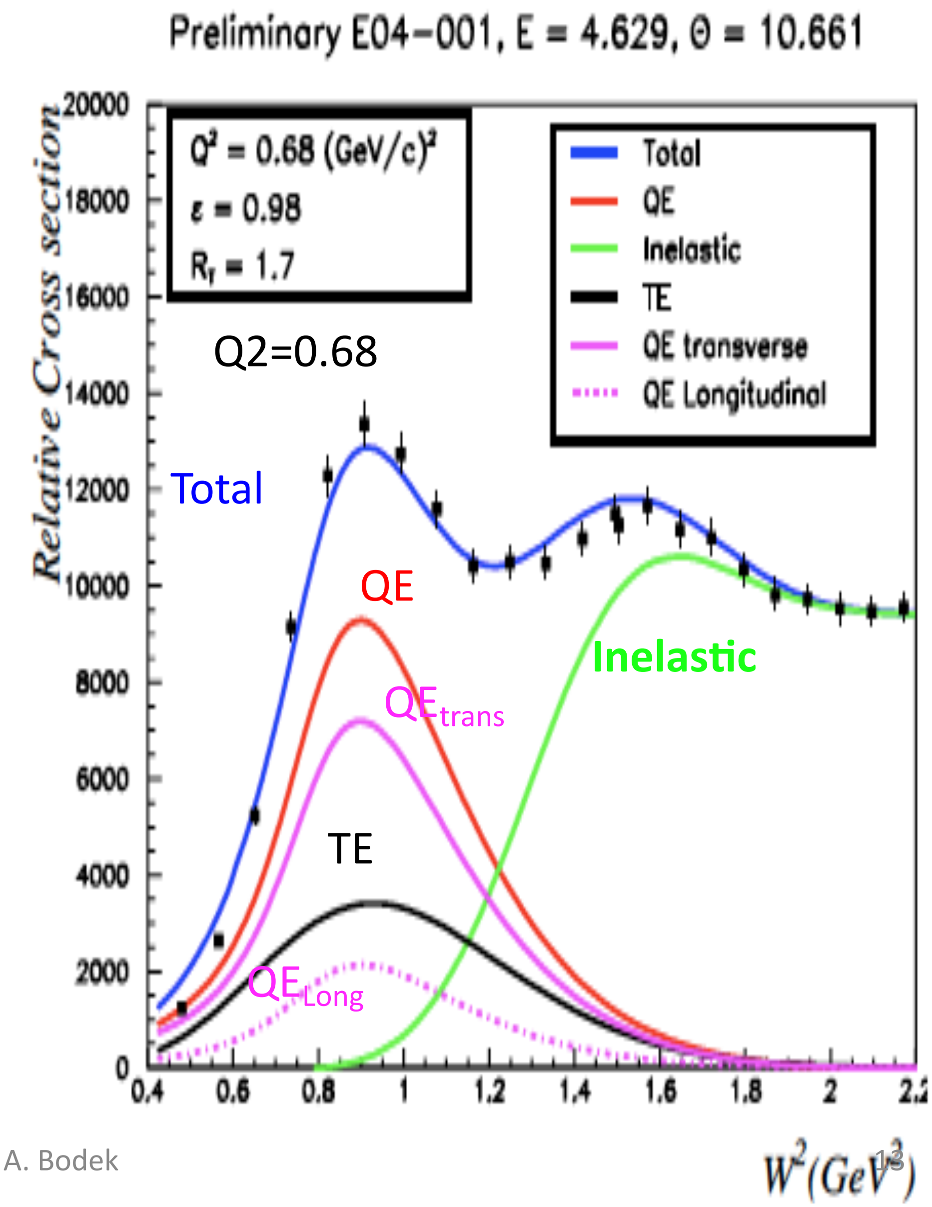
(In future we plan to improve it with updated L-T separated data from E04-001)

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

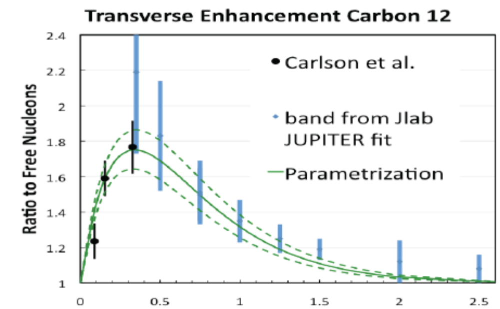
A spinoff of the fit is the TE component versus Q2

Extracting Transverse enhancement at Q^2>0.3 GeV2

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



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

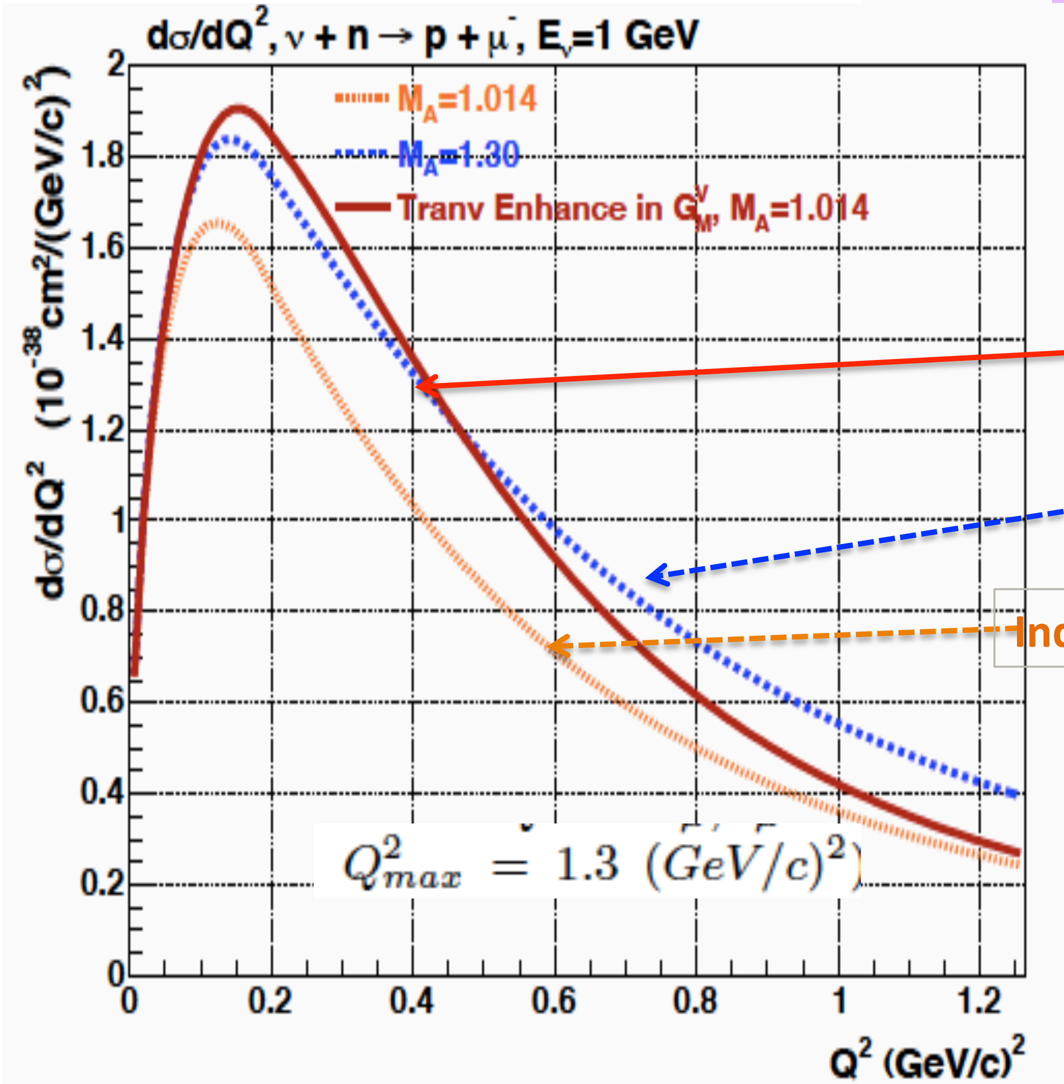
- We do not need a detailed specific model of MEC. -- Just CVC, so this is valid even if TE is not MEC (e.g. it can be any nuclear physics correction to the transverse cross section)

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

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

Predictions:

Low energy Carbon (~1 GeV)



At low energies: $d\sigma/dQ^2$

Q^2 range is limited

($0 < Q^2 < 1.3$ GeV^2)

transverse enhancement

looks similar to M_A=1.30

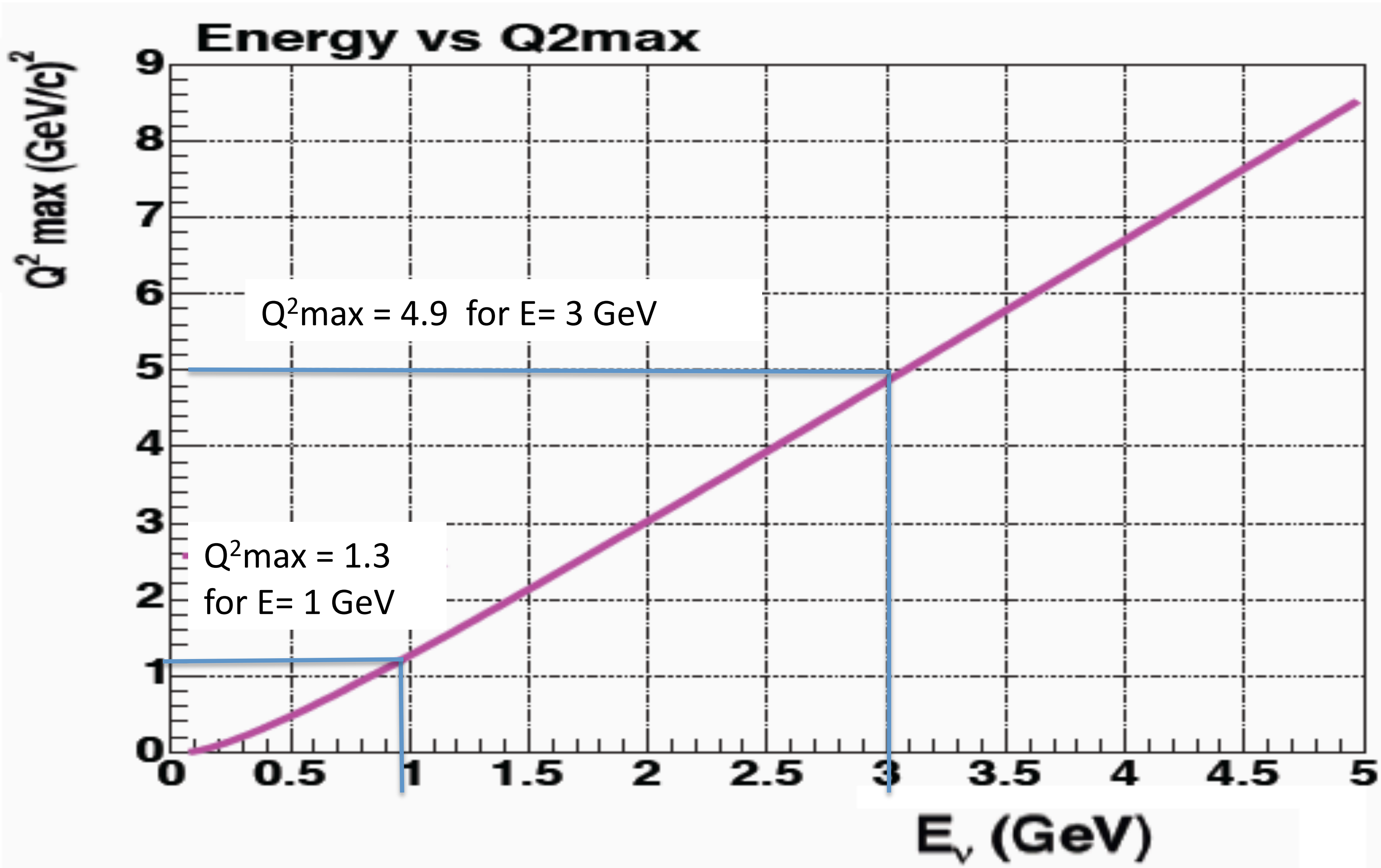
Independent nucleons with M_A=1.014

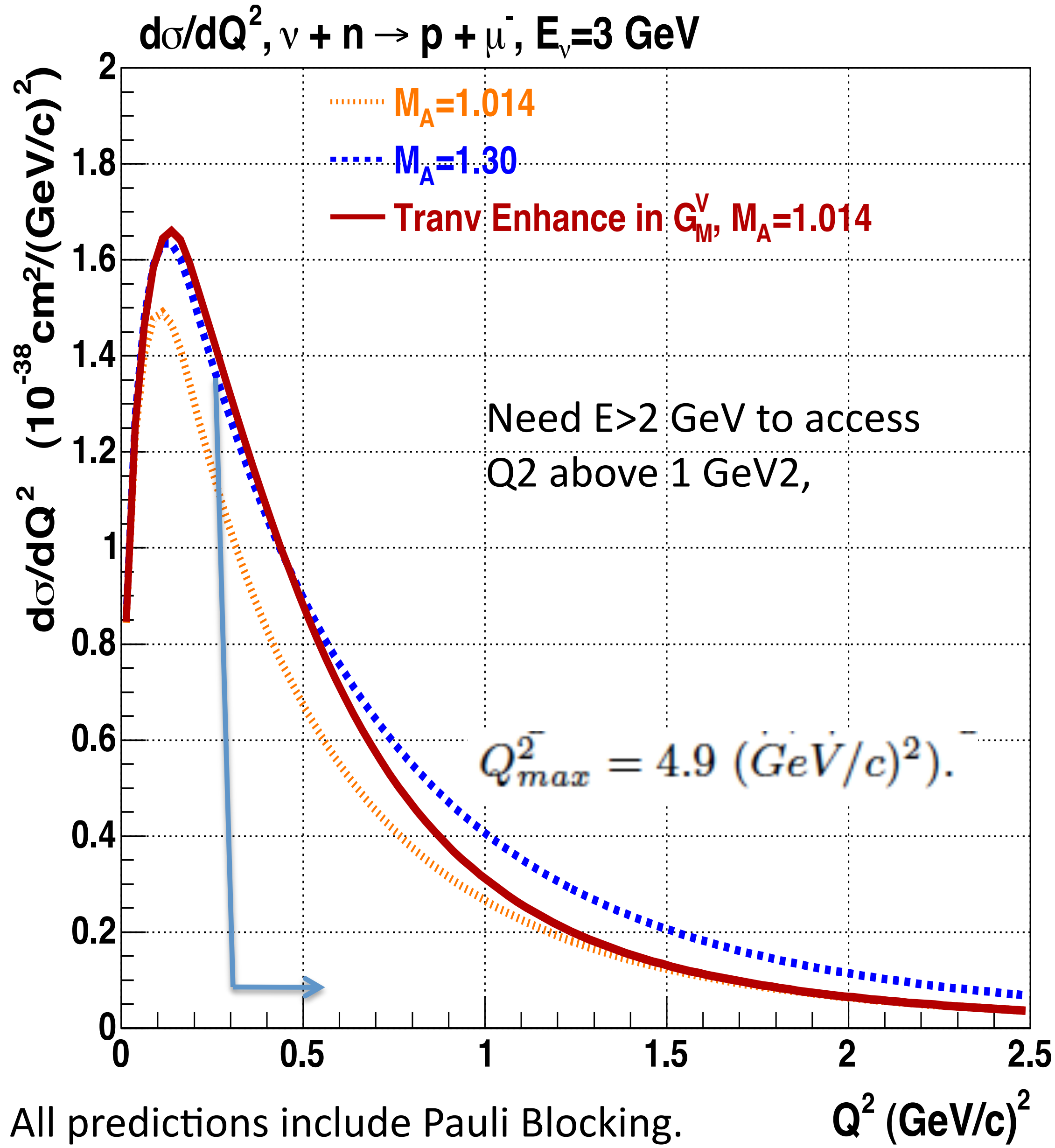
Q^2max = 1.3

All predictions include Pauli Blocking.

>>> MA is not large in nuclear targets

Lower energies have lower Q^2max, where the transverse enhancement is large.
Large difference in Q^2max between E=1 GeV and E= 3 GeV neutrino energies





All predictions include Pauli Blocking.

High energy experiments put a Q^2 cut to fit data in a region where there is no Pauli Blocking.

At high Q^2 transverse enhancement looks Like M_A<1.014 since dσ/dQ^2 transitions between M_A=1.30 curve and M_A=1.014 curve, so it is steeper than M_A=1.014 .

free nucleons

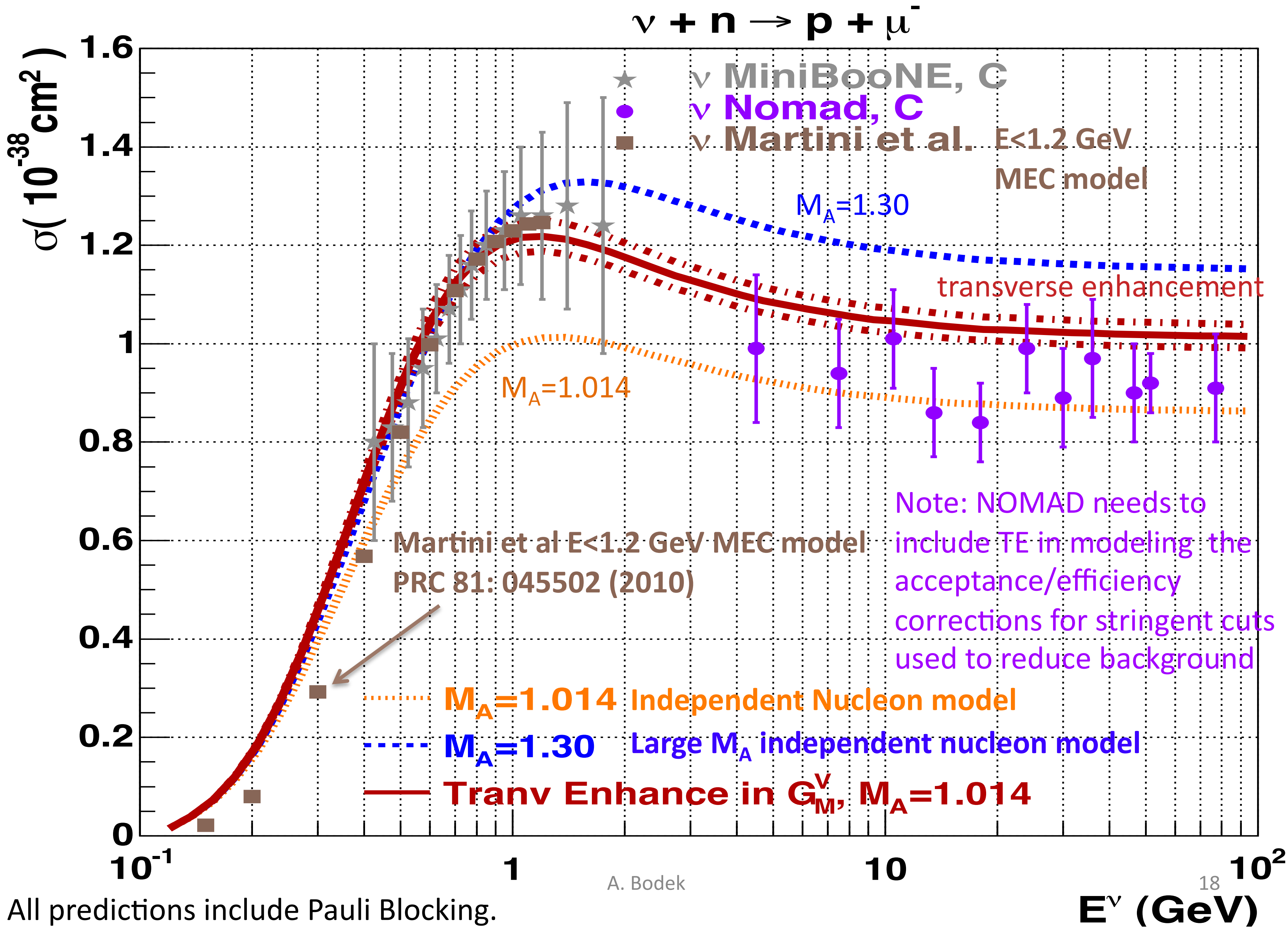
$$M_A^{free} = 1.014 \pm 0.014\ GeV$$

World average of all High energy neutrino experiments on nuclear targets is

M_A of 0.979 ± 0.016 GeV

Konstantin S. Kuzmin , Vladimir V. Lyubushkin, Vadim A. Naumov, Eur.Phys.J. C54 (2008) 517-538;

Total QE cross sections on Carbon (per neutron)



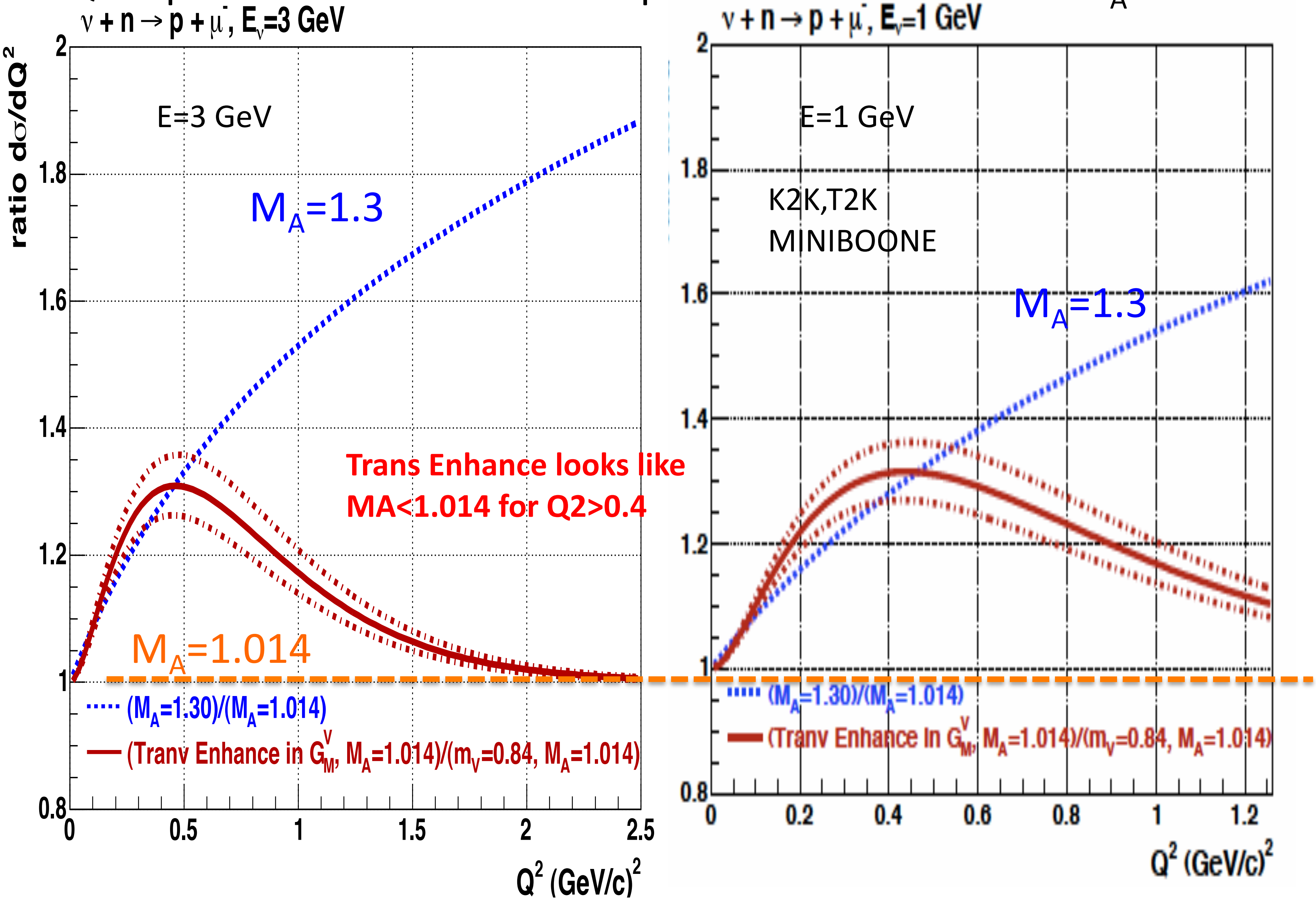
All predictions include Pauli Blocking.

Conclusions

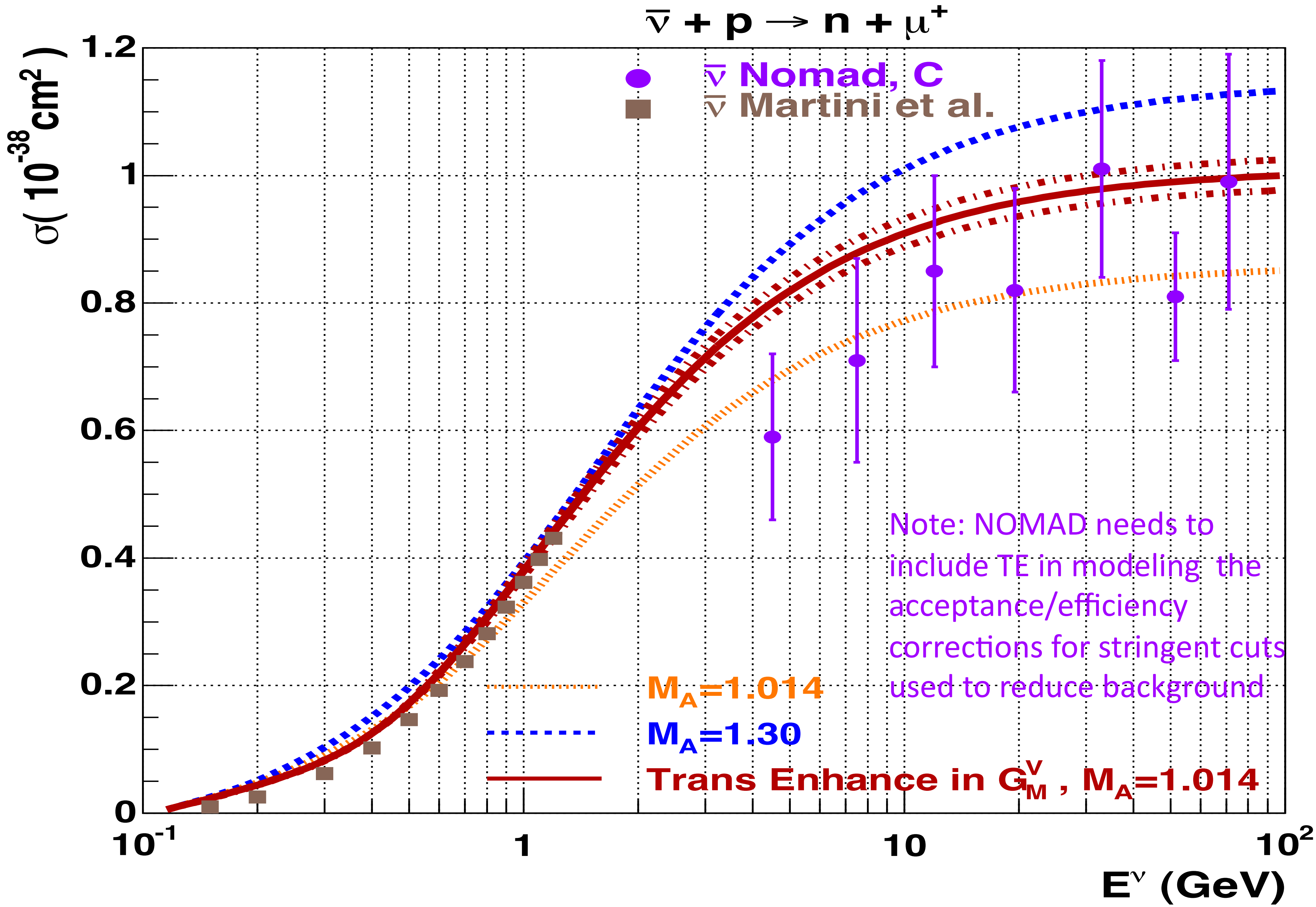
- The transverse enhancement (TE) observed in electron scattering experiments explains much of the " Axial Mass Anomaly". The enhancement is predominantly at low Q^2, so it has a greater effect on the cross sections at low energy.
- The same structure functions and form factors describe low energy and high energy data (as expected). Therefore, high energy experiments need to include TE in modeling acceptance/efficiency corrections.
- The reason for the difference in the fits to $d\sigma/dQ^2$ at low energy and high energy is the limited range of accessible Q^2 (Q^2max) for E<1 GeV.
- Including TE in existing neutrino MC generators is simple to do (by a modification of GMP and GMN for bound nucleons)
- More precise L and T vector structure functions and form factors on nuclear targets (and TE) will be available soon from Jlab JUPITER-Will provide much needed input to neutrino MC generators.
- TE should be clearly seen in QE $d\sigma/dQ2$ data currently collected by the MINERvA experiment at Fermilab over a wide range of energies
- More at: Bodek, Budd, Christy –arXiv:1106.0340[hep-ph]

Backup

Q^2 dependence of Ratio to Independent nucleons with M_A=1.014



All predictions include Pauli Blocking.



$\bar{\nu} + p \rightarrow n + \mu^+$
$\bar{\nu}$ Nomad, C
$\bar{\nu}$ Martini et al.
$\sigma(10^{-38}cm^2)$
1.2
1
0.8
0.6
0.4
0.2
0
10^{-1}
1
10
10^2
E^{ν} (GeV)
M_A=1.014
M_A=1.30
Trans Enhance in G_M^V , M_A=1.014
Note: NOMAD needs to include TE in modeling the acceptance/efficiency corrections for stringent cuts used to reduce background

σ_{Total}

$$\frac{d\sigma^{ud}}{dQ^2 d\nu} = S_{cos}\frac{1}{2E^2}\mathcal{W}_1\left[Q^2+m_\mu^2\right] \quad \sigma_1$$

$$+S_{cos}\mathcal{W}_2\left[(1-\frac{\nu}{E})-\frac{(Q^2+m_\mu^2)}{4E^2}\right] \quad \sigma_2$$

σ_{W_2}

$$+S_{cos}\mathcal{W}_3\left[\frac{Q^2}{2ME}-\frac{\nu}{4E}\frac{Q^2+m_\mu^2}{ME}\right] \quad \sigma_3$$

$$+S_{cos}\mathcal{W}_4\left[m_\mu^2\frac{(Q^2+m_\mu^2)}{4M^2E^2}\right] \quad \sigma_4$$

$$-S_{cos}\mathcal{W}_5\left[\frac{m_\mu^2}{ME}\right] \quad \sigma_5$$

$$W^{\nu-vector}_{1-Qelastic} = \delta(\nu-\frac{Q^2}{2M})\tau|\mathcal{G}^V_M(Q^2)|^2$$

$$W^{\nu-axial}_{1-Qelastic} = \delta(\nu-\frac{Q^2}{2M})(1+\tau)|\mathcal{F}_A(Q^2)|^2$$

$$W^{\nu-vector}_{2-Qelastic} = \delta(\nu-\frac{Q^2}{2M})|\mathcal{F}_V(Q^2)|^2$$

$$W^{\nu-axial}_{2-Qelastic} = \delta(\nu-\frac{Q^2}{2M})|\mathcal{F}_A(Q^2)|^2$$

$$W^{\nu}_{3-Qelastic} = \delta(\nu-\frac{Q^2}{2M})|2\mathcal{G}^V_M(Q^2)\mathcal{F}_A(Q^2)|$$

$$\mathcal{G}^V_E(Q^2) = G^p_E(Q^2) - G^n_E(Q^2),$$
$$\mathcal{G}^V_M(Q^2) = G^p_M(Q^2) - G^n_M(Q^2).$$

$$|\mathcal{F}_V(Q^2)|^2 = \frac{[\mathcal{G}^V_E(Q^2)]^2+\tau[\mathcal{G}^V_M(Q^2)]^2}{1+\tau}.$$

$$W_{1-Qelastic}^{\nu-vector} = \delta(\nu - \frac{Q^2}{2M})\tau|\mathcal{G}_M^V(Q^2)|^2$$

$$W_{1-Qelastic}^{\nu-axial} = \delta(\nu - \frac{Q^2}{2M})(1+\tau)|\mathcal{F}_A(Q^2)|^2$$

$$W_{2-Qelastic}^{\nu-vector} = \delta(\nu - \frac{Q^2}{2M})|\mathcal{F}_V(Q^2)|^2$$

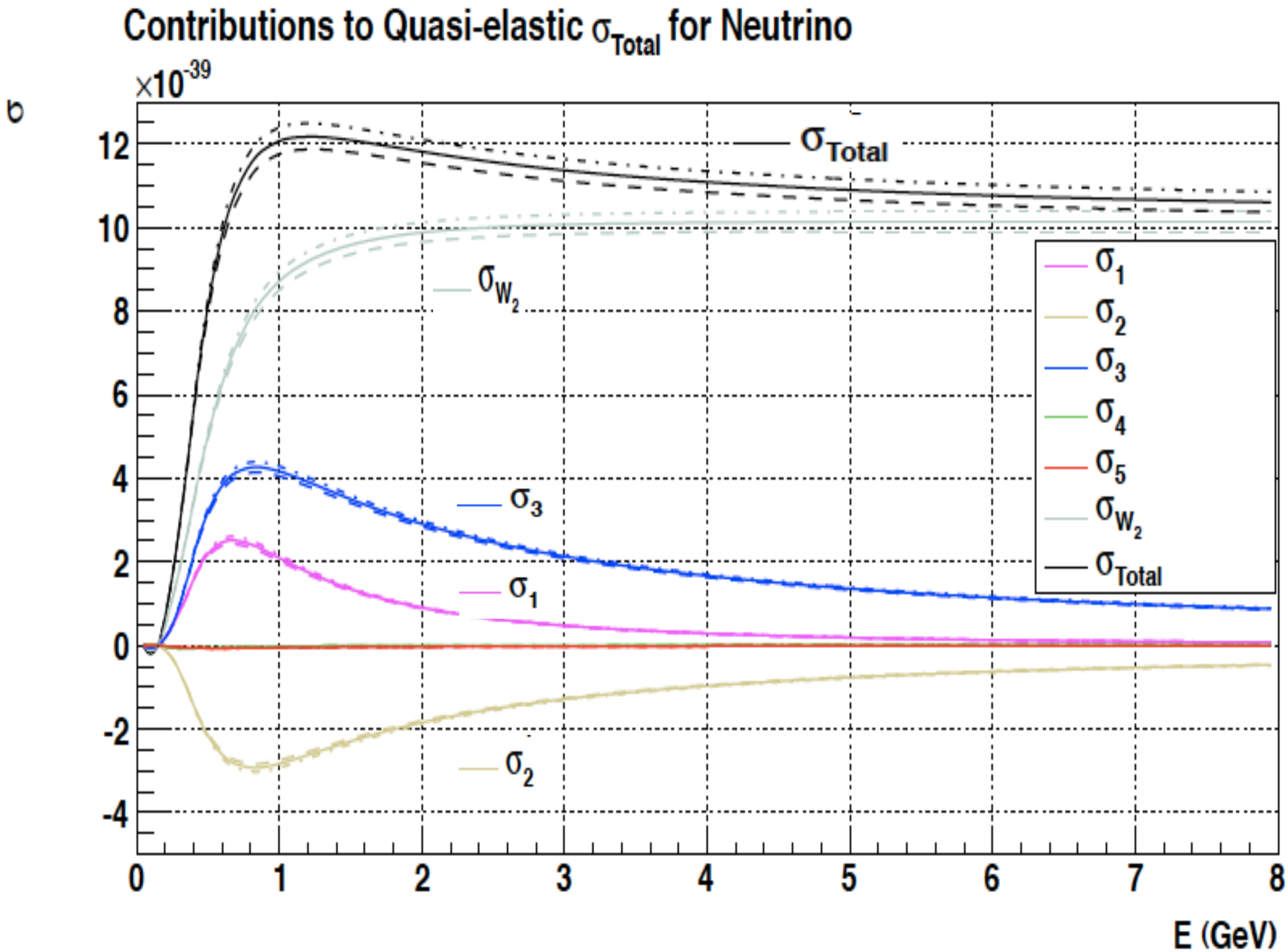
$$W_{2-Qelastic}^{\nu-axial} = \delta(\nu - \frac{Q^2}{2M})|\mathcal{F}_A(Q^2)|^2$$

$$W_{3-Qelastic}^{\nu} = \delta(\nu - \frac{Q^2}{2M})|2\mathcal{G}_M^V(Q^2)\mathcal{F}_A(Q^2)|$$

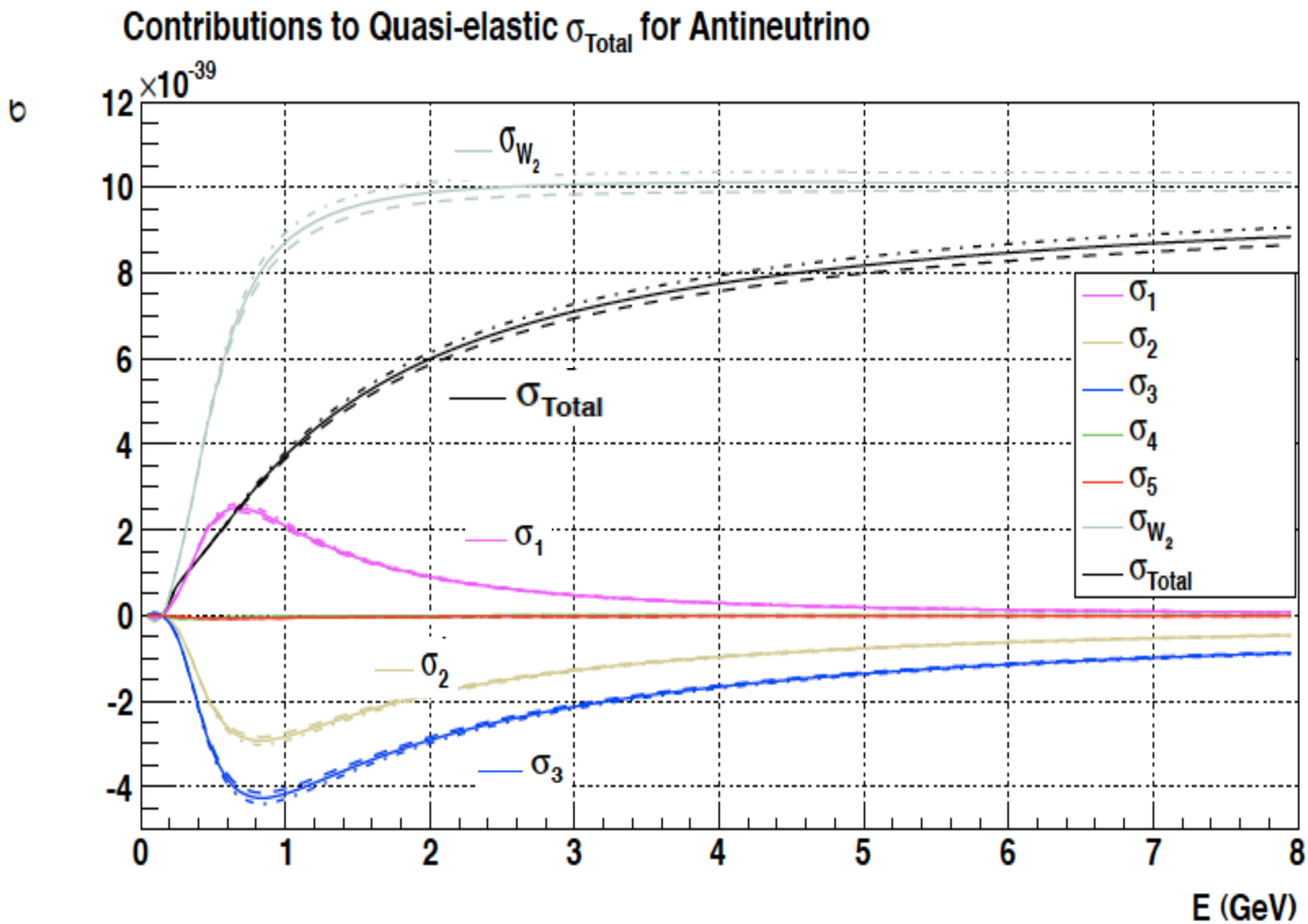
$$\mathcal{G}_E^V(Q^2) = G_E^p(Q^2) - G_E^n(Q^2),$$

$$\mathcal{G}_M^V(Q^2) = G_M^p(Q^2) - G_M^n(Q^2).$$

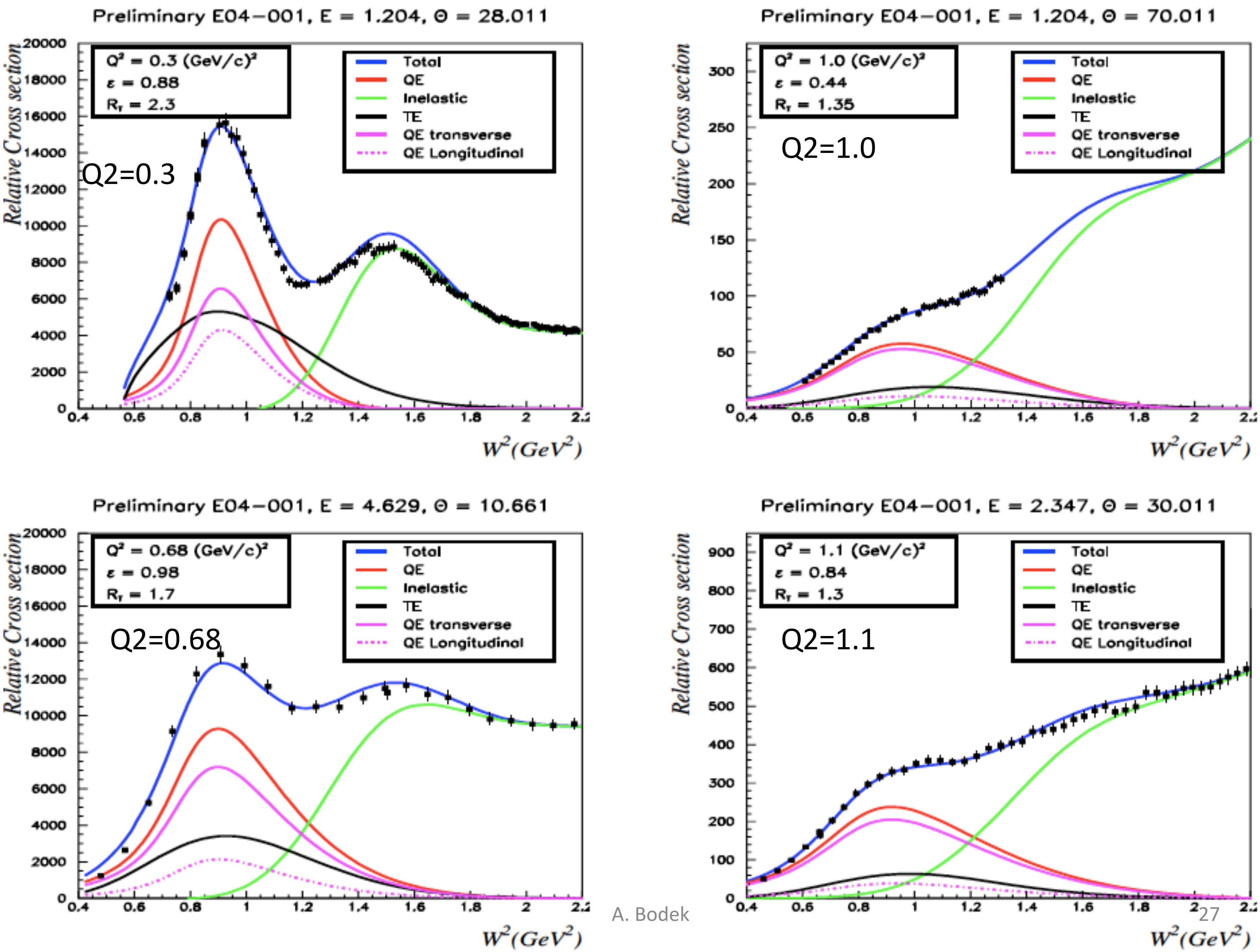
$$|\mathcal{F}_V(Q^2)|^2 = \frac{[\mathcal{G}_E^V(Q^2)]^2 + \tau[\mathcal{G}_M^V(Q^2)]^2}{1+\tau}.$$

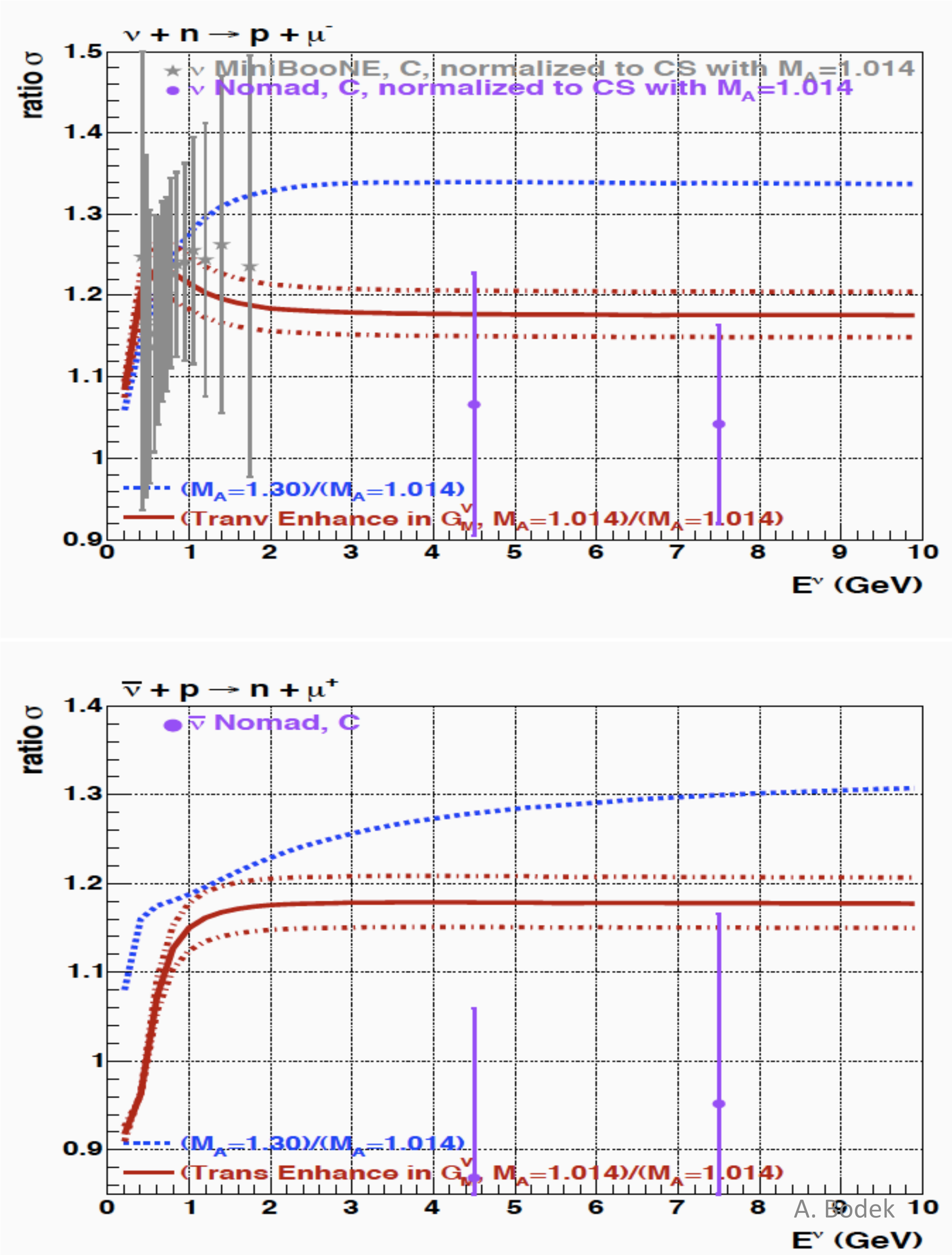


Contributions to Quasi-elastic σ_{Total} for Neutrino
σ
$\times 10^{-39}$
12
10
8
6
4
2
0
-2
-4
0
1
2
3
4
5
6
7
8
E (GeV)
σ_{Total}
σ_{W_2}
σ_3
σ_1
σ_2
σ_1
σ_2
σ_3
σ_4
σ_5
σ_{W_2}
σ_{Total}



Contributions to Quasi-elastic σ_{Total} for Antineutrino
σ
$\times 10^{-39}$
12
10
8
6
4
2
0
-2
-4
0
1
2
3
4
5
6
7
8
E (GeV)
σ_{W_2}
σ_{Total}
σ_1
σ_2
σ_3
σ_1
σ_2
σ_3
σ_4
σ_5
σ_{W_2}
σ_{Total}


Preliminary E04−001, E = 1.204, Θ = 28.011
Q² = 0.3 (GeV/c)²
ε = 0.88
R_T = 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
R_T = 1.35
Q2=1.0
Preliminary E04−001, E = 4.629, Θ = 10.661
Q² = 0.68 (GeV/c)²
ε = 0.98
R_T = 1.7
Q2=0.68
Preliminary E04−001, E = 2.347, Θ = 30.011
Q² = 1.1 (GeV/c)²
ε = 0.84
R_T = 1.3
Q2=1.1



Ratio of cross sections to independent nucleon model with free nucleon form factors and M_A=1.014

M_A=1.3 predicts 35% increase in cross sections for neutrinos and 30% for antineutrinos at high energies (> 3 GeV)

Transverse Enhancement predicts 15% increase in cross sections for both neutrinos and antineutrinos at high energies (>3 GeV)

At low energies (<1 GeV) , Transverse Enhancement predicts that the increase in antineutrinos is smaller than the increase for neutrinos.

All predictions include Pauli Blocking.

A. Bodek, S. Avvakumov, R. Bradford, and H. Budd, Eur. Phys. J. C53, 349 (2008).
BBBA

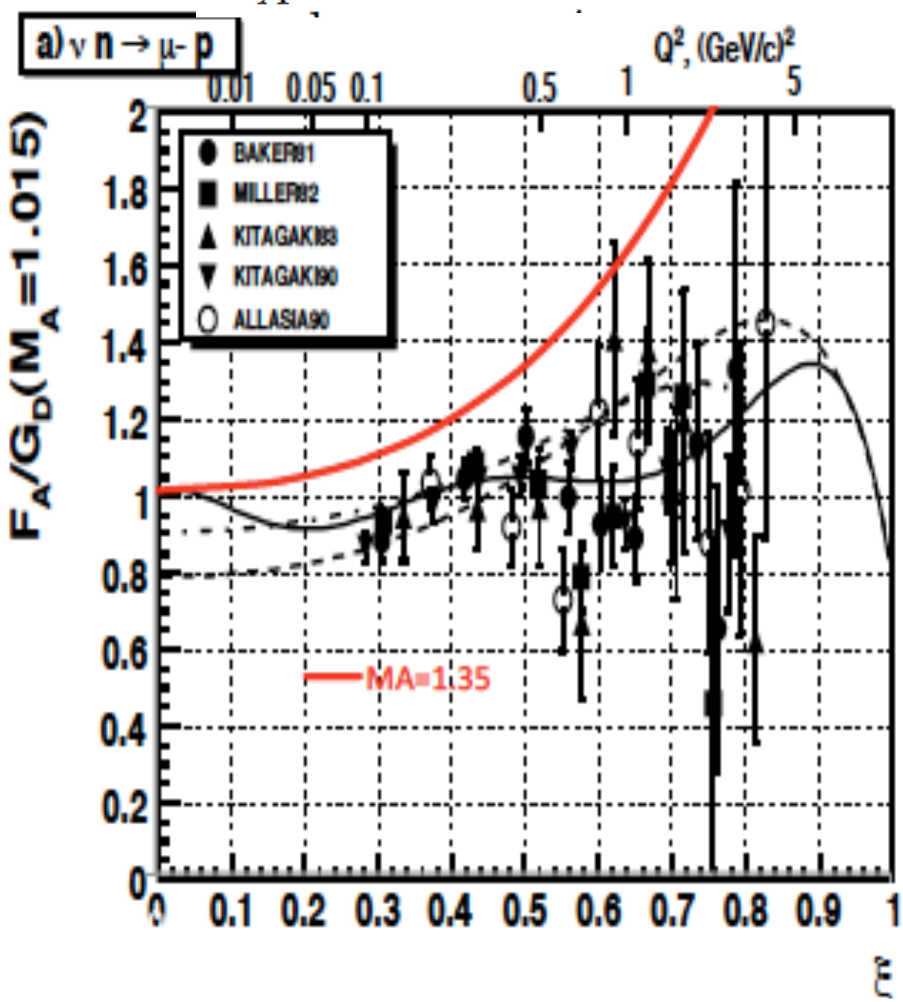
World Average Axial Form Factor measurements on Hydrogen and deuterium

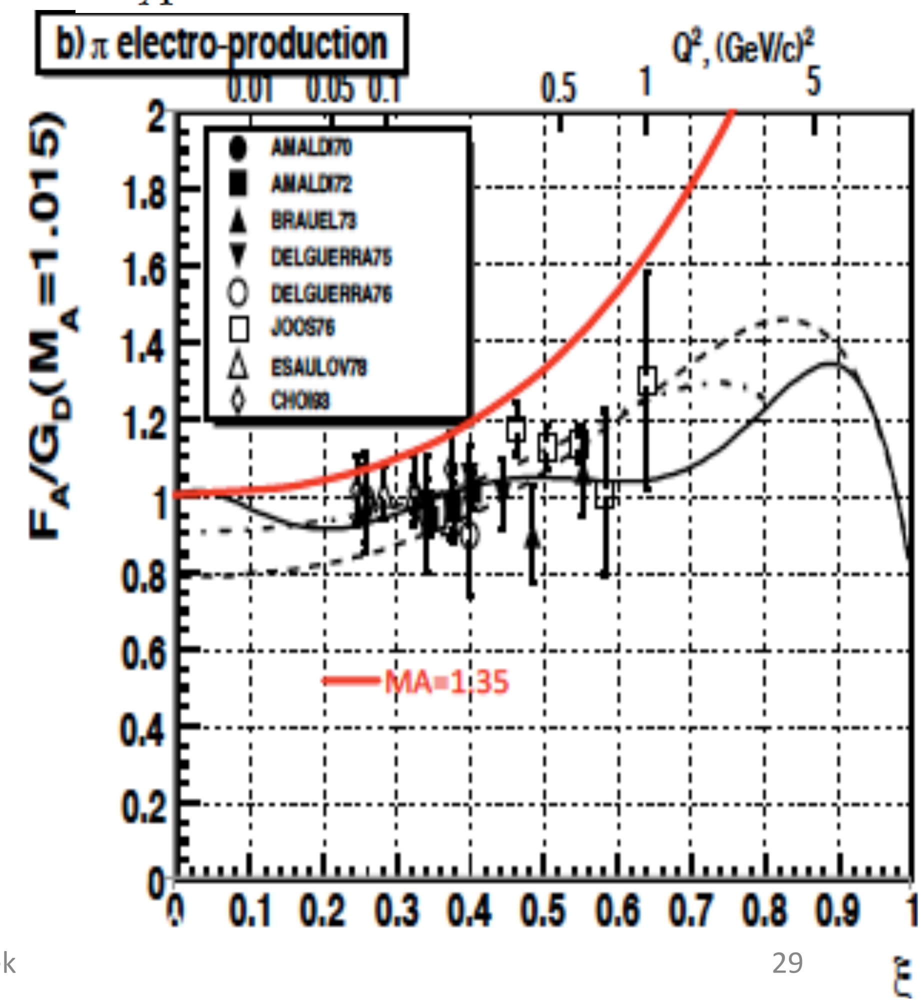
$M_A^{free} = 1.014 \pm 0.014 \ GeV$

$G_D^A(Q^2) = \frac{-1.267}{(1+Q^2/M_A^2)^2}$ with $M_A = 1.015 \ GeV$.

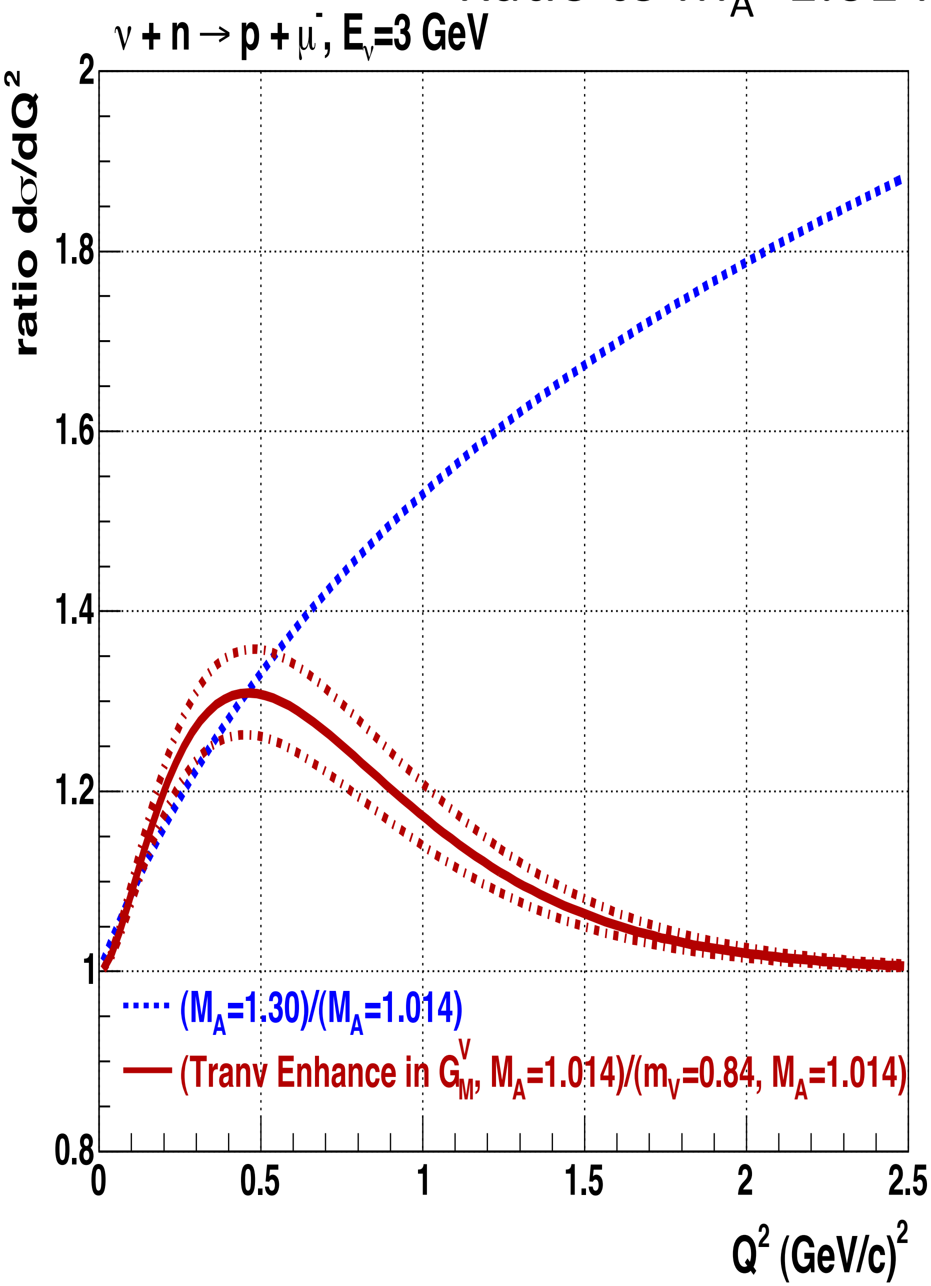
$M_A^{\nu_\mu,\bar{\nu}_\mu} = 1.016 \pm 0.026 \ GeV$

$M_A^{pion} = 1.014 \pm 0.016 \ GeV$





Ratio to M_A=1.014 (mostly independent of energy.



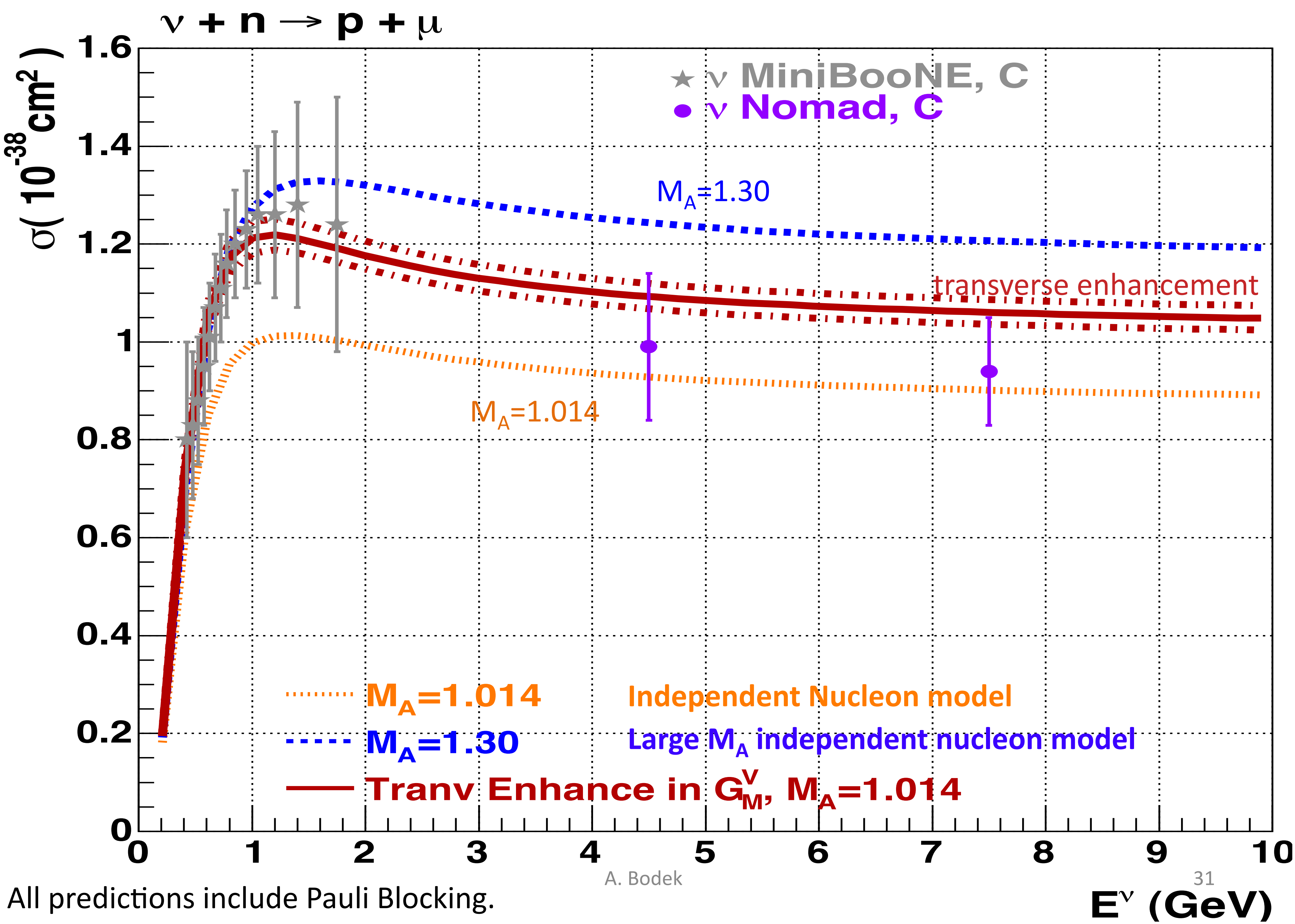
Q2 max = 3 GeV2 for E=2 GeV.

Plotting the ratio of dN/dQ2 (without even knowing the flux in detail) to dN/dQ2 for MA=1.014 should look like this plot (as long as data for neutrino energies below 2 GeV is removed).

The small energy dependent corrections an be included with a rudimentary knowledge of the flux.

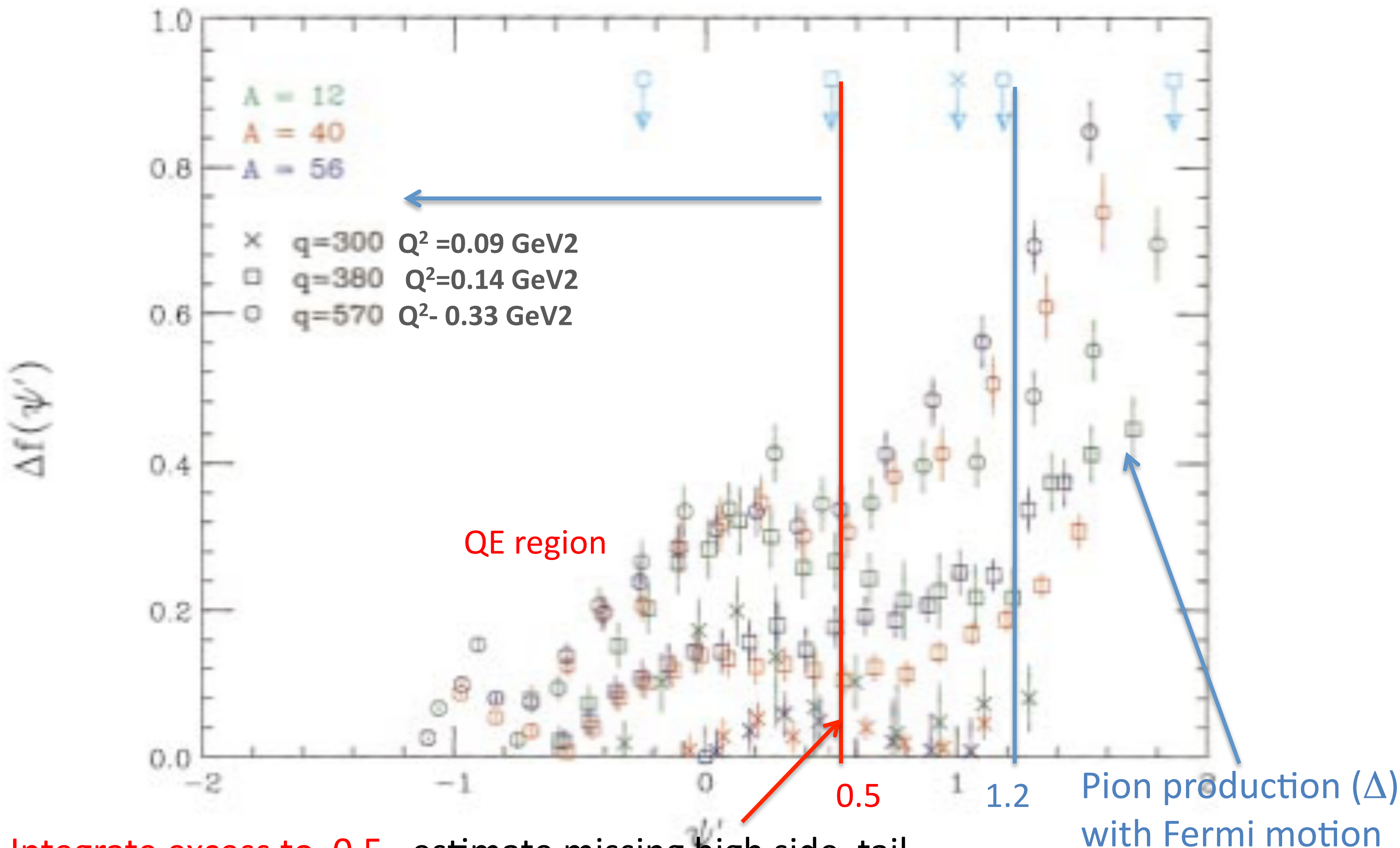
This can be tested in MINERvA (easier to do with neutrinos then with antineutrinos)

Total QE cross sections on Carbon (per neutron)



All predictions include Pauli Blocking.

Transverse Excess =Transverse response *minus* longitudinal response.



Integrate excess to 0.5, estimate missing high side tail, extract ratio R_T (ratio to universal response function) and study its Q^2 dependence

RADIATIVE CORRECTIONS

In order to do the radiative corrections for all Jlab's experiments one needs to know electron scattering cross sections over a wide range of energies and Q2.

Bosted and Christy published a fit that describes e-H and e-D data in the Jlab range (using data from a wide range of experiments)

The Bosted-Christy fits were extended to fit nuclear targets by Bosted and Mamyan. Data from several experiments on nuclear targets are included in the fits, including preliminary data from Jlab E04-001, the QE region is described using super-scaling model of Sick, Donnelly, Maieron (nucl-th/0109032).