Survey of neutrino-*nucleus* interactions

Main goals:

Reviewing neutrino-nucleus scattering with an emphasis on tackling the language of other communities:

a) Electron scattering community
b) Neutrino community
c) Nuclear structure community
d) High energy / particle physics community
e) Monte Carlo and / or experimental community

Identify the common assumptions which simplify the calculations

Identify places for improvement

Language and questions (theory)

Inclusive versus Exclusive reactions

Elastic versus Quasielastic (and Inelastic) scattering

(Nucleon/Nuclear) Trasparency

Factorization in general and scaling in ***inclusive*** scattering

Language and questions (experiment)

Cross-sections corresponding to events with/without one charged lepton in the final state and contributions from events with:

Everything but pions in the final state ("QE inclusive")

And contributions to this case with:

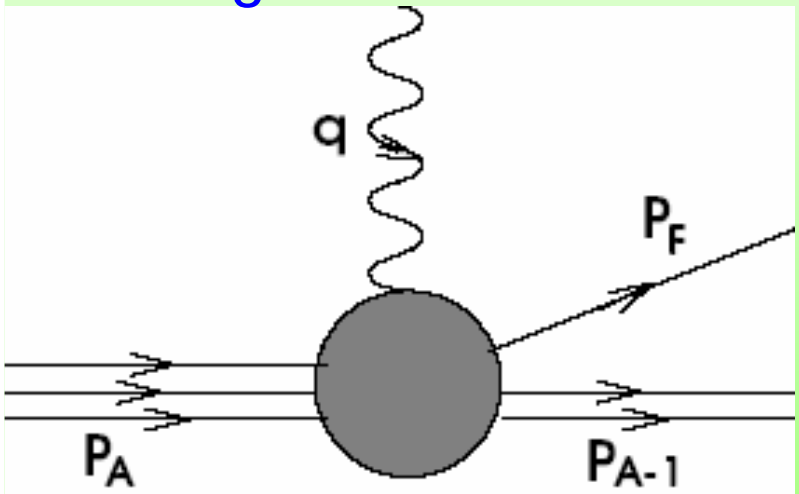
i) At least un proton in the final state

ii) One proton and just one proton in the final state

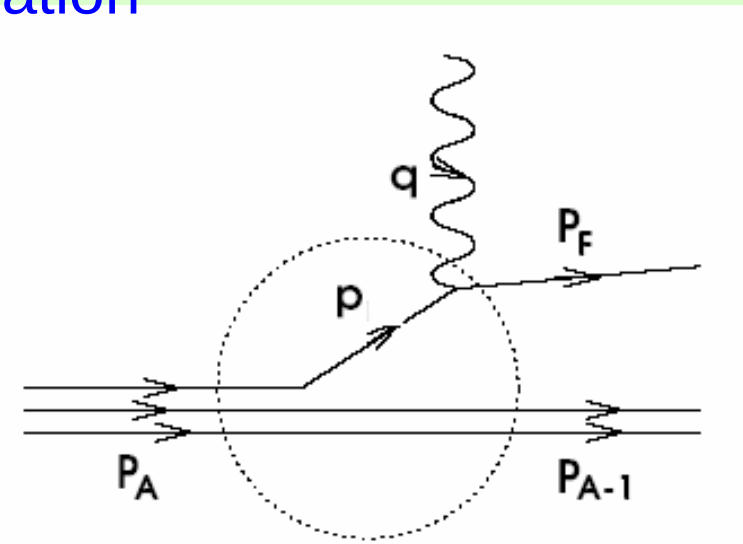
iii) One proton and things that do not yield signal in the detector in the final state

From neutrino-nucleon to neutrino-nucleus
OVERVIEW OF THE IA (ingredients)

Simple: One boson exchange:



Even simpler: Impulse Approximation



$$J_N^\mu(\omega,\vec{q}) = \int d\vec{p}\,\bar{\psi}_F(\vec{p}+\vec{q})\,\hat{J}_N^\mu(\omega,\vec{q})\psi_B(\vec{p})$$

Current operators and Form Factors (vector)

Off-shell nucleons, several non-equivalent choices for the vector current. Use CVC and take vector FF from electron scattering exps.

$$\Gamma_1^\mu(p_f,p_i) = \gamma^\mu G_M(Q^2) - \frac{P^\mu}{2m}F_2(Q^2)$$

$$\Gamma_2^\mu(p_f,p_i) = \gamma^\mu F_1(Q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2m}F_2(Q^2)$$

$$\Gamma_3^\mu(p_f,p_i) = \frac{P^\mu}{2m}F_1(Q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2m}G_M(Q^2)$$

For CC, one should care about a possible $F_3(Q_2)$ q_μ term. F_3 should vanish if $P^2_i=P^2_f$ as for instance for neutral or EM currents and may have a definite form (see for instance JH Koch, V Pascalutsa, S. Scherer PRC65 045202 (2002)). Expect effect of order m_μ^2/Q^2 for intermediate Q^2

Current operators and Form Factors (axial)

For the axial current, taken from electron scattering PV and neutrino-nucleon scattering data, beta decay, PCAC, somewhat constrained by radiative muon capture data (induced pseudoscalar factor)

The vector current is ‘protected’ while the axial one is not

$$ {}_N\left\langle p' \left| J_\mu^{NC} \right| p \right\rangle_N = \bar{u}(p') \left[\gamma_\mu F_1^{Z,N}(Q^2) + i\frac{\sigma_{\mu\nu}q^\nu}{2M} F_2^{Z,N}(Q^2) + \gamma_\mu\gamma_5 G_A^{Z,N}(Q^2) + \frac{q_\mu}{M}\gamma_5 G_P^{Z,N}(Q^2) \right] u(p) $$

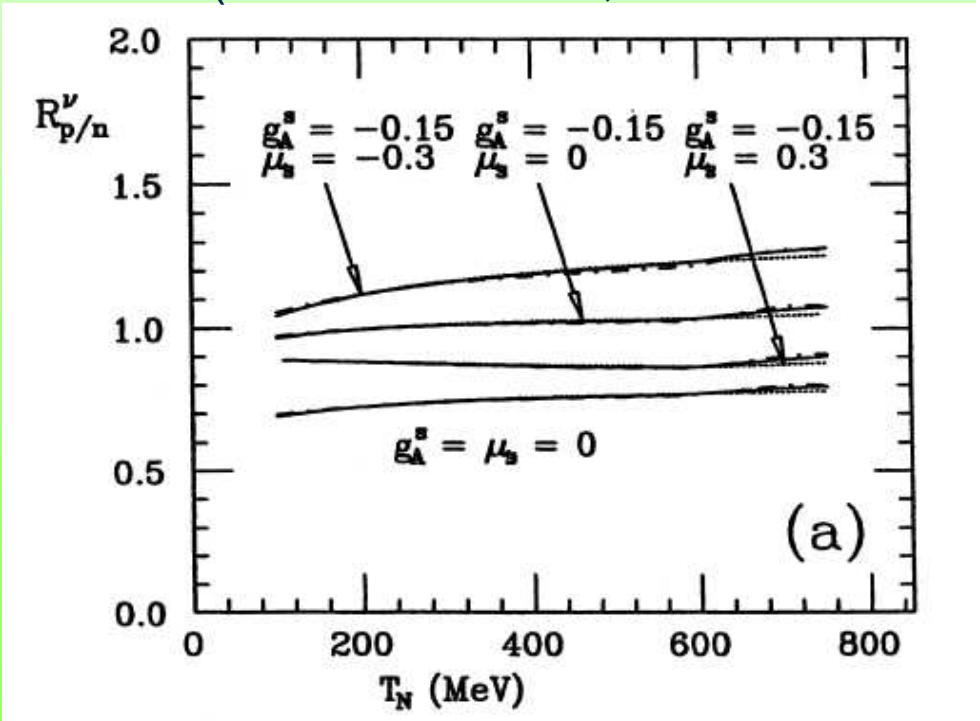
For NC, one should care about strangeness in the FF. PV electron scattering and neutrino-nucleon scattering, set some limits on this strange contribution, but there is a large correlation among strangeness contribution to electric, magnetic and axial FF

Measuring strangeness content

a) Obtain more PV measurements, perhaps on a non-isoscalar target

b) Measure ratios and/or differences of NC p/n yields. For instance for carbon and 1 GeV neutrino (WM Alberico et al, PLB 438 (1998) 9)

$$\mathscr{R}^{\nu(\bar{\nu})}_{p/n} = \frac{(d\sigma/dT_N)_{\nu(\bar{\nu}),p}}{(d\sigma/dT_N)_{\nu(\bar{\nu}),n}}$$



We expected data on p/n NC knock-out in carbon from SLND. Did they come out?

Measuring strangeness content

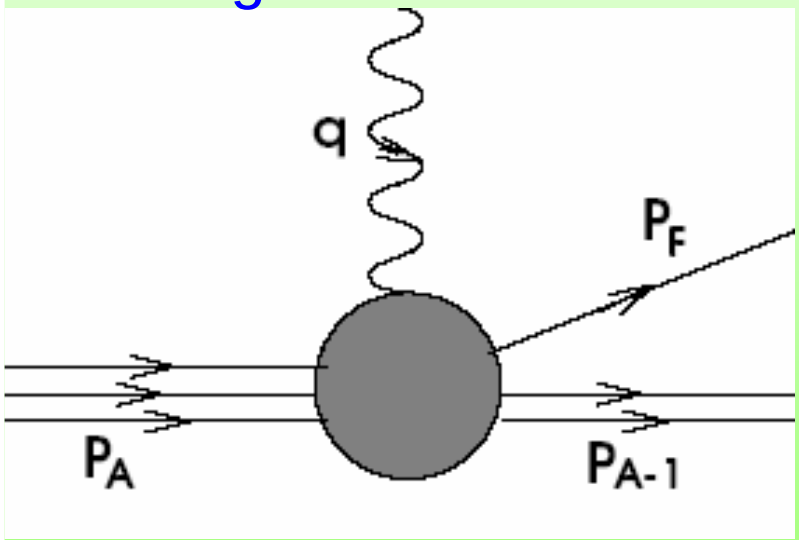
c) Measure ratios of NC/CC differences of p/n yields (Paschos-Wolfestein relation) WM Alberico et al. Z. für Physik C70, 463 (1996), Nucl.Phys. A651, 277 (1999)

$$\mathcal{A}_p(Q^2) = \frac{\left(\frac{d\sigma}{dQ^2}\right)_{\nu p\to\nu p} - \left(\frac{d\sigma}{dQ^2}\right)_{\bar{\nu} p\to\bar{\nu} p}}{\left(\frac{d\sigma}{dQ^2}\right)_{\nu n\to\mu^- p} - \left(\frac{d\sigma}{dQ^2}\right)_{\bar{\nu} p\to\mu^+ n}}$$

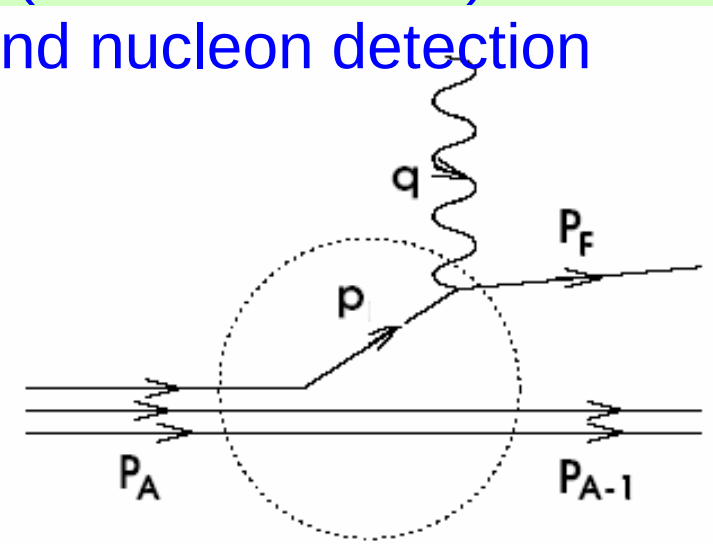
It is a somewhat difficult observable. It has been recently revived by the Ghent group (C.Praet, N.Jachowicz, J.Ryckebusch PRC74, 065501 (2006) ; N. Jachowicz et al. PRC76, 055501 (2008))

From neutrino-nucleon to neutrino-nucleus
OVERVIEW OF THE IA (ingredients)

Simple: One boson exchange:



Even simpler: Impulse Approximation, the interaction takes place with one nucleon, the one that is “detected”/considered. We will assume (for the moment) both lepton and nucleon detection

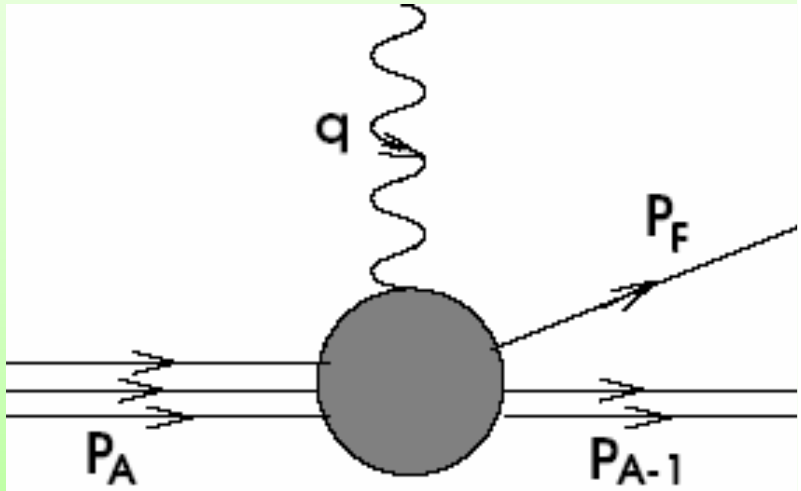


$$J_N^\mu(\omega,\vec{q}) = \int d\vec{p}\bar{\psi}_F(\vec{p}+\vec{q})\hat{J}_N^\mu(\omega,\vec{q})\psi_B(\vec{p})$$

OVERVIEW OF THE IA (ingredients)

1) Weak interacting probe (e^-,ν_e ...). It allows for the simplest approach: single boson (photon, $W^{\S}$,Z^0) exchange

2) Thus, the dependence on the kinematics of the exchanged boson can be extracted. For unpolarized and in plane electron scattering, this means:



$$\frac{d\sigma}{d\Omega_e d\varepsilon' d\Omega_F} = K\sigma_{Mott} f_{rec}\left[v_L R^L + v_T R^T + v_{TL} R^{TL}\cos\phi_F + v_{TT} R^{TT}\cos 2\phi_F\right]$$

One-boson exchange approximation yields, for the most general case:

$$\frac{d\sigma}{d\varepsilon_f d\Omega_f d\Omega_F} = \frac{E_F p_F}{(2\pi)^3}\sigma_M f_{rec}\frac{1}{2}\left\{v_L\left(R^L + R_n^L\widehat{S}_n\right) + v_T\left(R^T + R_n^T\widehat{S}_n\right)\right.$$
$$+ v_{TL}\left[\left(R^{TL} + R_n^{TL}\widehat{S}_n\right)\cos\phi_F + \left(R_l^{TL}\widehat{S}_l + R_s^{TL}\widehat{S}_s\right)\sin\phi_F\right]$$
$$+ v_{TT}\left[\left(R^{TT} + R_n^{TT}\widehat{S}_n\right)\cos 2\phi_F + \left(R_l^{TT}\widehat{S}_l + R_s^{TT}\widehat{S}_s\right)\sin 2\phi_F\right]$$
$$+ h\left\{v_{TL'}\left[\left(R_l^{TL'}\widehat{S}_l + R_s^{TL'}\widehat{S}_s\right)\cos\phi_F + \left(R^{TL'} + R_n^{TL'}\widehat{S}_n\right)\sin\phi_F\right]\right.$$
$$\left.\left. + v_{T'}\left[R_l^{T'}\widehat{S}_l + R_s^{T'}\widehat{S}_s\right]\right\}\right\},$$

R (response) functions are proportional to the Hadronic tensor $W^{\mu\nu}$

$$W^{\mu\nu} = \frac{1}{2j_b+1}\sum_{\mu_b} J^{\mu *}(\omega,\mathbf{q})J^{\nu}(\omega,\mathbf{q}).$$

The one-boson exchange approximation allows us to decouple the direct dependence on the *energy* and *scattering angle* of the probe *via* the Mott cross-section for electrons or the equivalent expressions for neutrinos

$$\left(d\sigma^{Z^0/W^\pm}\right)_{\text{Free}} = \delta^{(4)}(k_i^\mu - k_f^\mu + P_I^\mu - P_F^\mu)\,\sigma^{Z^0/W^\pm}\,\frac{1}{4\epsilon_f^2 E_I E_F}\,\omega_{\mu\nu}W^{\mu\nu}\,d^3\vec{P}_F d^3\vec{k}_f$$

The hadronic part does not need to be computed at every point. Folding with neutrino energy is much simplified

$$\sigma^{Z^0} = 16\,\epsilon_f^2\cos^2(\theta/2)\left[\frac{g^2}{4\pi}\right]^2$$

$$\sigma^{W^\pm} = 16 k_f^2\left[\frac{g^2}{4\pi}\right]^2$$

$$\omega_L W_L = \frac{1}{4\epsilon_i k_f}\Bigg\{\left[(\epsilon_i+\epsilon_f)^2 - |\vec{k}|^2 - m_l^2\right]|\rho|^2 + \left[\frac{(\epsilon_i^2-k_f^2)^2}{|\vec{k}|^2} - \omega^2 + m_l^2\right]|J_k|^2 - \left[\frac{2(\epsilon_i+e_f)(\epsilon_i^2-k_f^2)}{|\vec{k}|} - 2\omega|\vec{k}|\right] Re\,(\rho^* J_k)\Bigg\}$$

$$\omega_T W_T = \Bigg\{\cancel{\frac{\epsilon_i k_f \sin^2\theta}{2|\vec{k}|^2}\cos(2\phi_F)\left(|J_\parallel|^2 - |J_\perp|^2\right)} + \left[\frac{\epsilon_i k_f \sin^2\theta}{2|\vec{k}|^2} - \frac{1}{2}\left(\frac{-\epsilon_f}{k_f} + \cos\theta\right)\right]\left(|J_\parallel|^2 + |J_\perp|^2\right)\Bigg\}$$

$$\omega_{TT'} W_{TT'} = -\frac{1}{|\vec{k}|}\left(\frac{\epsilon_i\epsilon_f}{k_f} + k_f - (\epsilon_i+\epsilon_f)\cos\theta\right) Im\,(J_\parallel J_\perp^*)$$

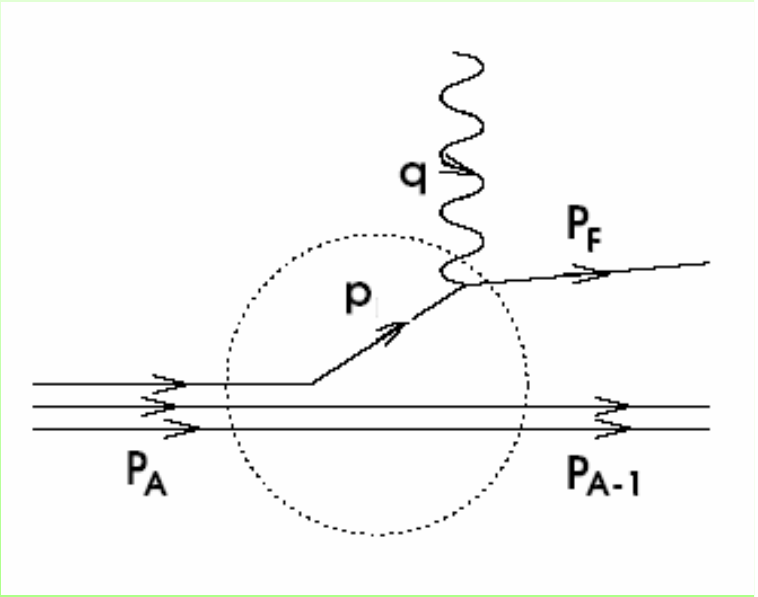
L, T and TT' are the only responses that contribute if no nucleon is observed

OVERVIEW OF THE IA
(more ingredients)

3) Remember Impulse Approximation

A weak probe will interact with similar probability with both surface nucleons and deep ones

For QE conditions and large q (a few hundreds of MeV), all nucleons contribute to the cross-section incoherently. The nuclear current is obtained as a sum over individual single-nucleon currents:



$$J_N^\mu(\omega,\vec{q}) = \int d\vec{p}\,\bar{\psi}_F(\vec{p}+\vec{q})\,\hat{J}_N^\mu(\omega,\vec{q})\psi_B(\vec{p})$$

SUMMARIZING SO FAR

- Under one boson exchange, direct dependence on energy and scattering angle is factored out
- Under Impulse Approximation, nuclear response is built from the sum of individual nucleon responses. Final phase space includes one nucleon knock-out factors
- Responses depend only on q and ω transferred to the nucleus, even when FSI or other effects are considered
- Besides current operators and form factors, the IA calculation needs some wave functions to compute the matrix element, for the initial and the final nucleons

Just as an illustration, we will take the simplest ingredients: mean field solutions for the initial and final nucleon wave functions. If relativistic, we will talk about RMF or relativistic mean field

Relativistic Mean Field

$$(\tilde{E}\gamma_0 - \vec{p}\cdot\vec{\gamma} - \tilde{M})\psi = 0$$

$$\tilde{E} = E - V(r)$$
$$\tilde{M} = M - S(r)$$

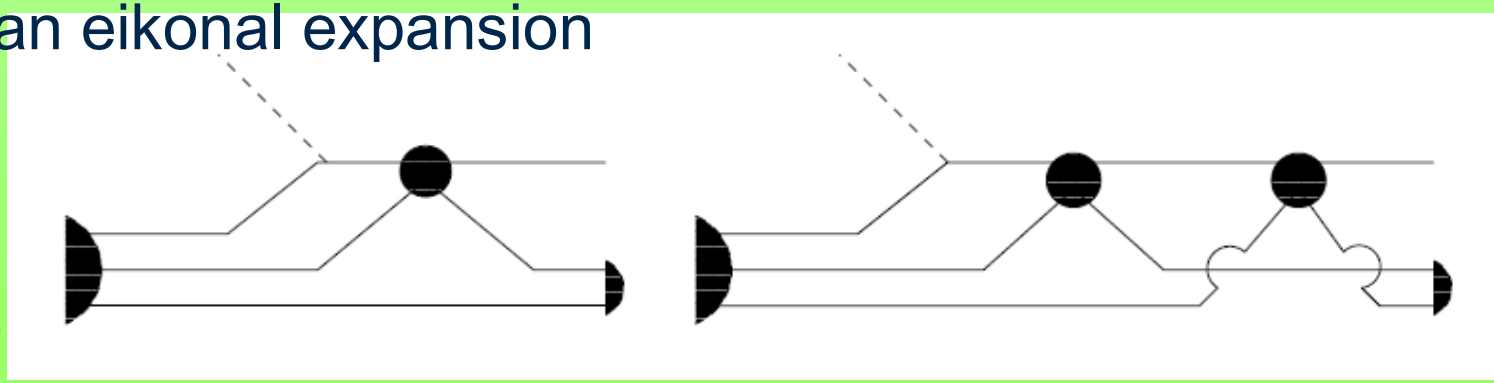
- Solve a Dirac-like equation
- Bound state: For instance, phenomenological σ-ω lagrangeans (Serot and Walecka model) at mean field level
:
- Final State: Put the nucleon in the continuum and with potentials (distorted wave function). Solve Dirac equation for an scattering state. This can be done in a partial wave expansion or RDWIA (“*exact*” but computationally demanding) or within eikonal (or eikonal+Glauber) approaches, which are good approximations and are even more demanding, computationally speaking
- Use a scattering potential adequate to the process we want to describe. It may be taken from phenomenology

Let's take a moment to describe the nucleon in the final state

•In a very simple scheme we consider that the nucleon does not feels the residual nucleus. It does not scatter and travels free, described by a plane wave. These are RPWIA or plane wave results in general

•Further, one can think of an expansion in the number of interactions of the nucleon and the residual system. PWIA would be the zeroth order. This is very useful in light systems

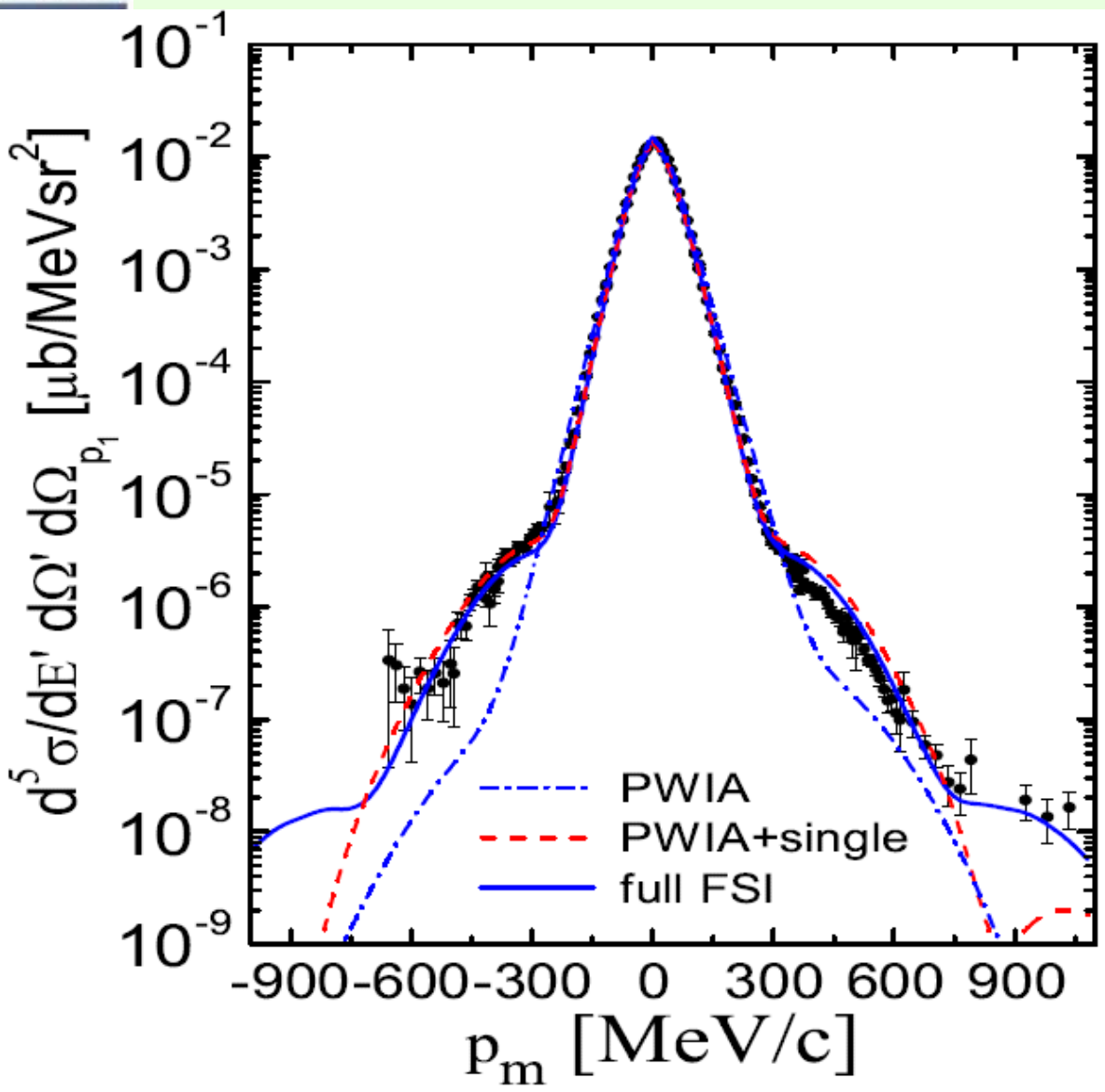
•One, two (shown in the figures for a given channel) and more interactions can be computed in a diagrammatical way, or upon an eikonal expansion



Describing the final state in ^{3}He(e,e'p)d

Data: M.M. Ravchev, PRL 94 (2005) 192302

Full theoretical calculation of the overlap from Faddev calculations+eikonal/ Glauber treatment of the detected nucleon with single and double ("full calculation") rescattering terms included. No free parameters in this result Phys. Rev. Lett. 100, 122301 (2008)

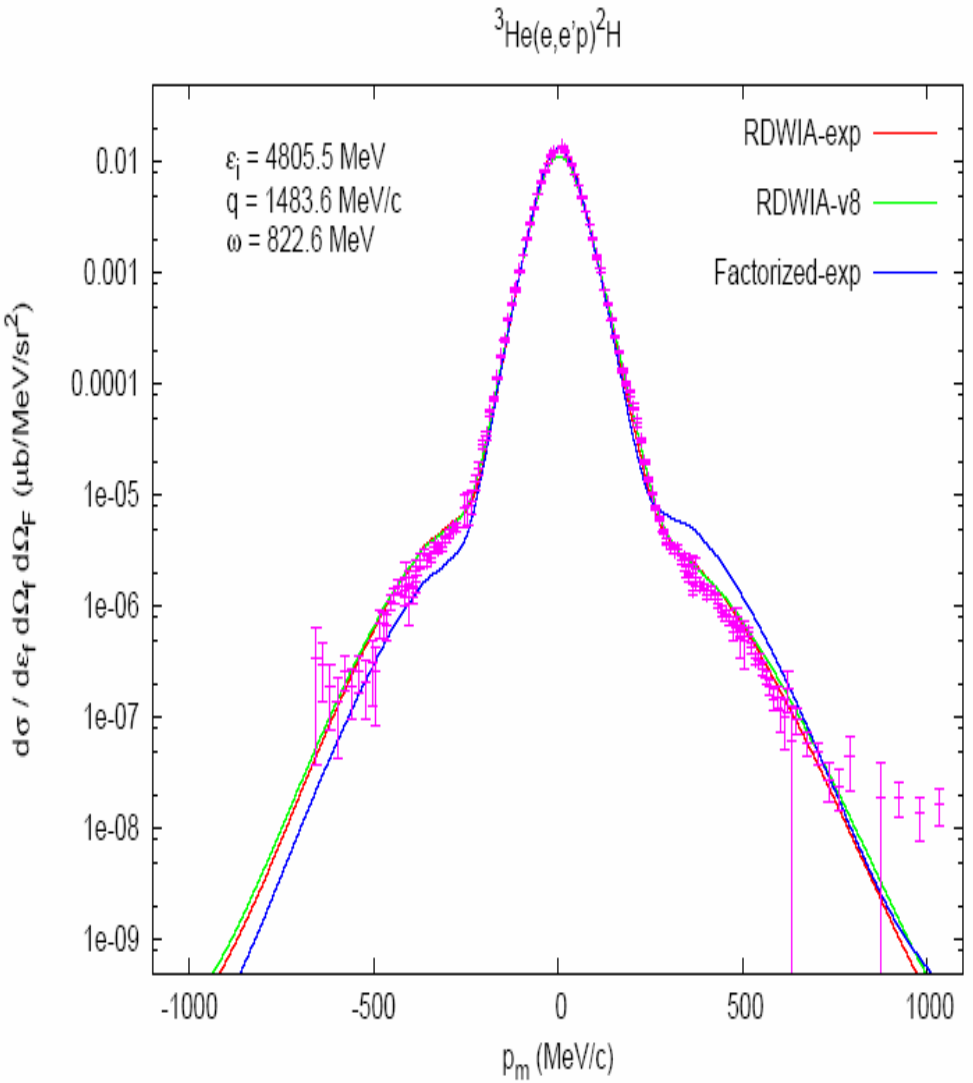


Describing the final state

- Rescattered and direct terms interfere, destructively for small missing momentum and constructively at large missing momentum. It is not just the result of summing up cross-sections yielding a free nucleon in the final state plus the cross section with one rescattering in the final state, this would miss interferences
- The plane wave calculation may not be equal to the contribution to the total number of events coming from the cases where the nucleon does not interact in the final state
- Comparison of theory to experiment was simple in this exercise because the experiment separated the channels very cleanly (only two body breakup was included in these data)

Describing the final state

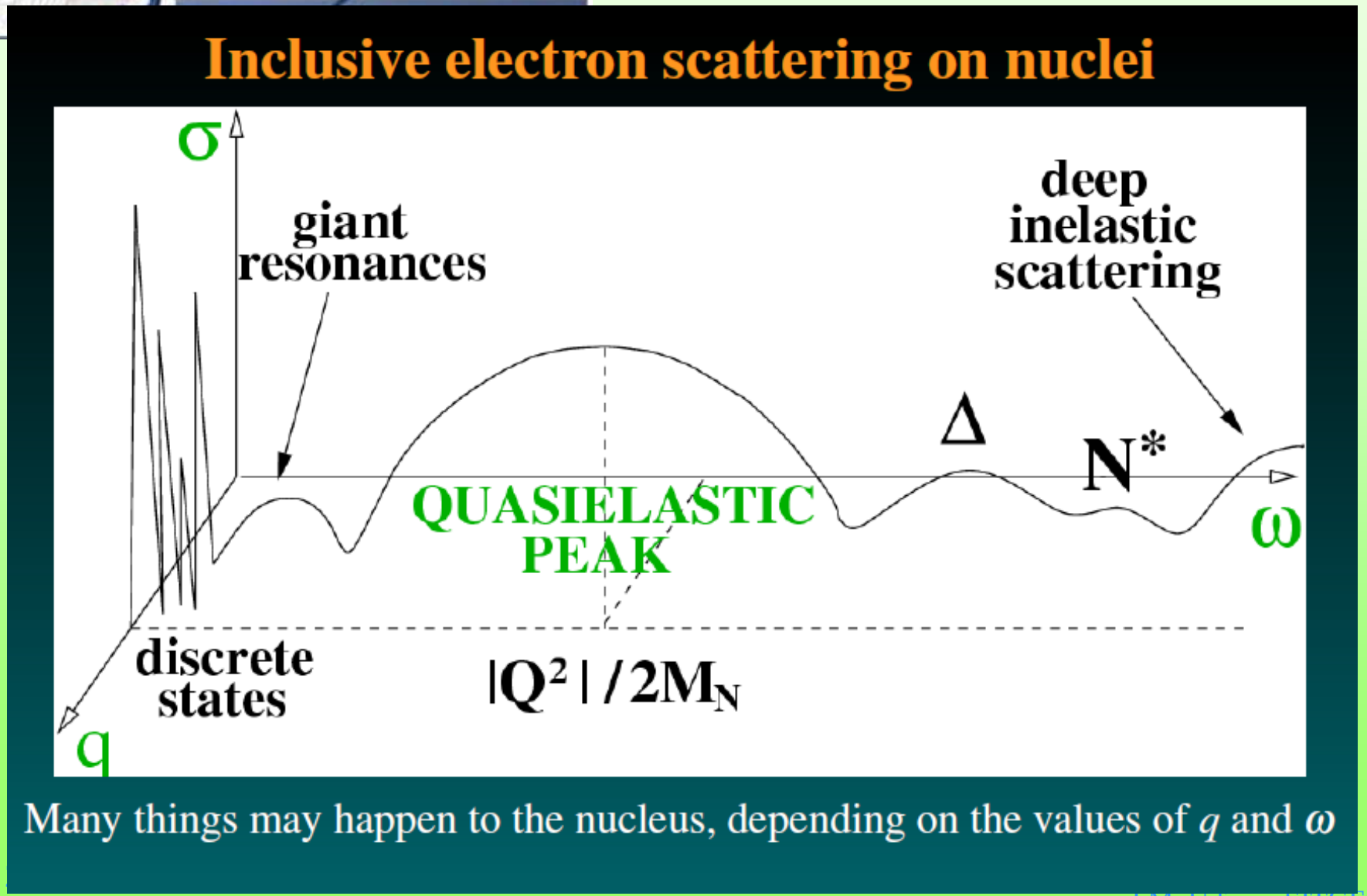
•For not so light systems, truncation of the rescattering series may not be such a good approximation. Summation of the whole rescattering series is possible under certain approximations. For instance, one can build optical potentials, that eventually are fit to proton elastic data. This does a similarly good job, as shown in the picture



Thus, which is the problem with the final state?

- The problem is that we do not always know which is the final state
- From the theory side, there are simple cases that can be computed more easily, such as the elastic channel or the fully inclusive case. Otherwise, all the relevant diagrams or processes have to be considered
- Alternatively, one may look at data from similar reactions and try to extract information for a different reaction

Survey of neutrino-*nucleus* interactions



An useful tool in the interpretation of experiments: the factorization approach

It implies that the same **effective** operator as for free nucleons is employed in computing the matrix element. It implies on-shell spinors (but is not enough) to guarantee factorization. Even in the nonrelativistic case, one has to ensure that the sum on nucleon angular momentum is the same as for free spinors. This is not true in general when FSI are present

In short, factorization is recovered in the cross-sections if there is no LS coupling in the initial or final nucleon and one uses on-shell nucleons

Factorization? Recall:

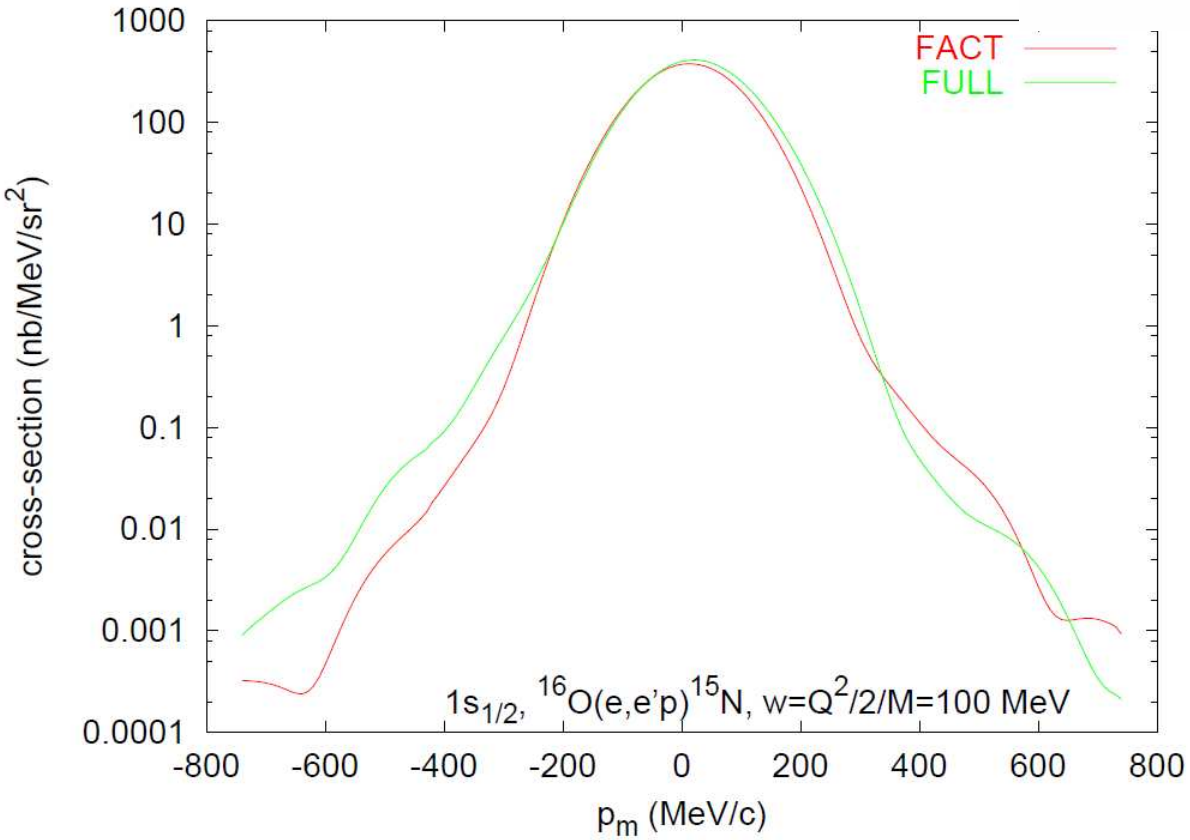
•It implies that the same **effective** 2 £ 2 operator as for free nucleons is employed. This hypothesis is strongly broken by the enhancement of the lower components in RMF. This is a factorization-breaking effect not present in nonrelativistic models. Using on-shell spinors is required (but is not enough) to guarantee factorization

•It requires additional approximations to the Relativistic Impulse Approximation ones. Even in the nonrelativistic case, one has to ensure that the sum on nucleon angular momentum is the same as for free spinors. This is not true in general when FSI are present

•In summary, for cross-sections, factorization is recovered if there is no LS coupling in the initial or final nucleon and no off-shell nucleons

Factorized approach

$$\frac{d^5\sigma}{d\Omega_e d\varepsilon' d\Omega_F} = K\sigma_{ep}S(E_m,\vec{p}_m) \qquad \rho^{exp}(\mathbf{p}_m) = \frac{\left(\frac{d\sigma}{d\varepsilon_f d\Omega_f d\Omega_F}\right)^{exp}}{E_F p_F f_{rec}\,\sigma_{ep}}\,.$$



Within this approach, one does not compute the matrix element of the current operator, but instead one takes the elementary lepton-nucleon cross-section into play

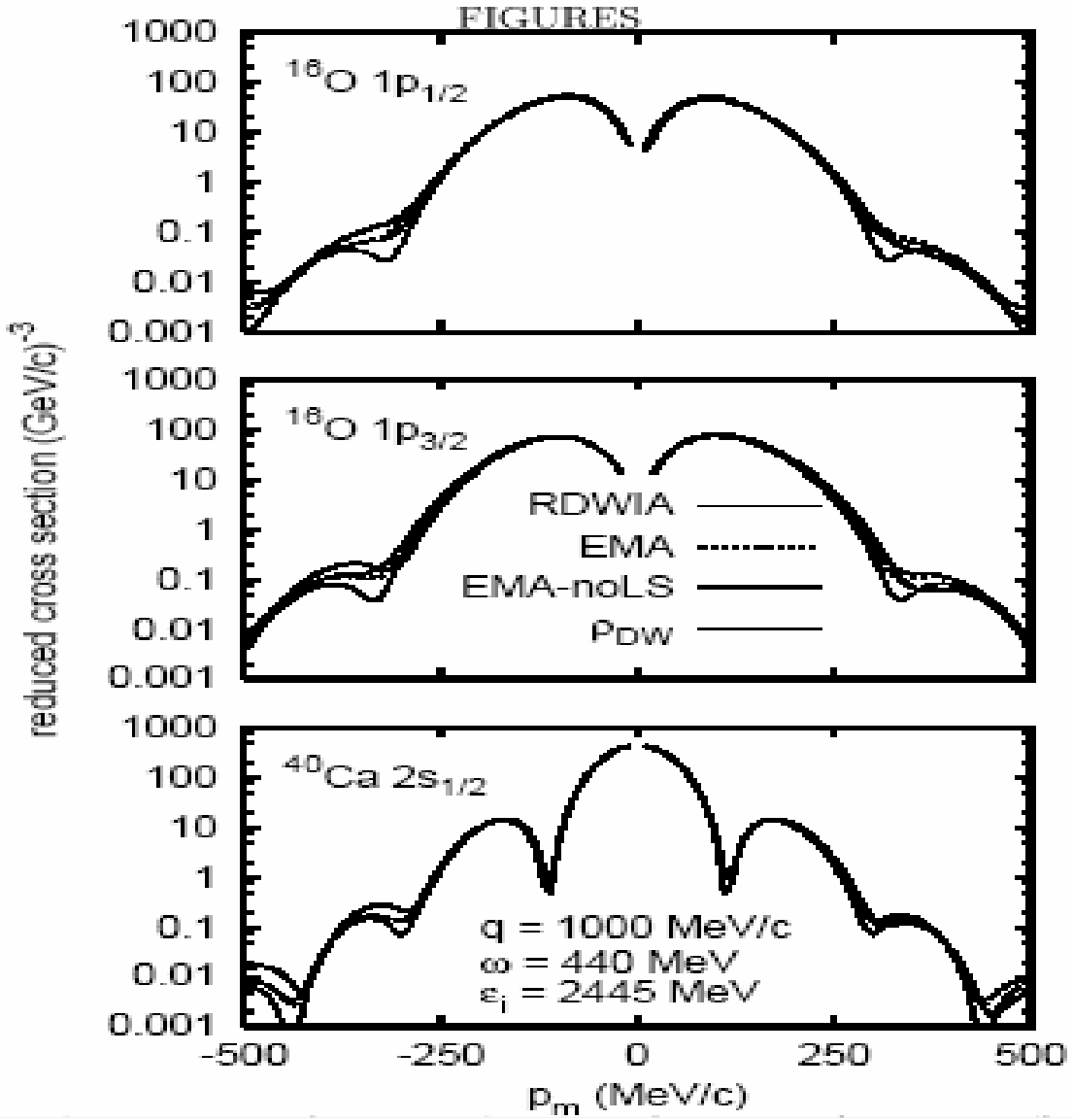
•Under factorization, the cross-section splits completely into an elementary lepton-nucleon part, depending on the interaction, and a nuclear part (spectral function) that depends on E_m and p_m and that is completely independent on the nature of the probe

•The single-nucleon responses are in principle different for each kind of lepton, due to different structure of the elementary current operator, but the nuclear response is the same if factorization is (nearly) recovered

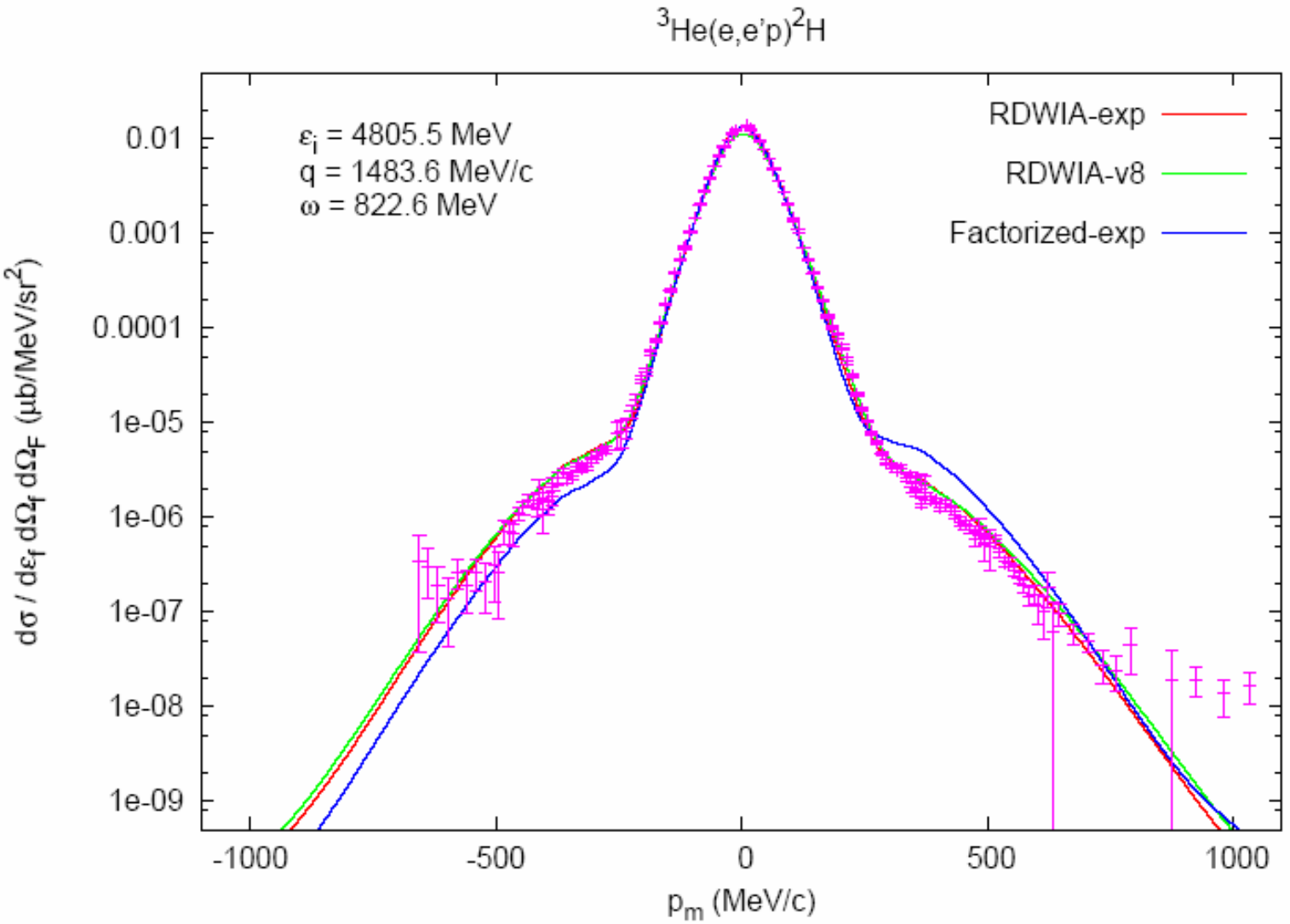
•Let's put it in another way: The properties of the nuclear response are (to a large extent) independent on the probe that excites such response, if factorization is recovered

•The applicability of nuclear responses from one reaction to another depends on the extent that factorization is fulfilled

RMF: Small non-factorization effects in the cross-sections for moderate p_m

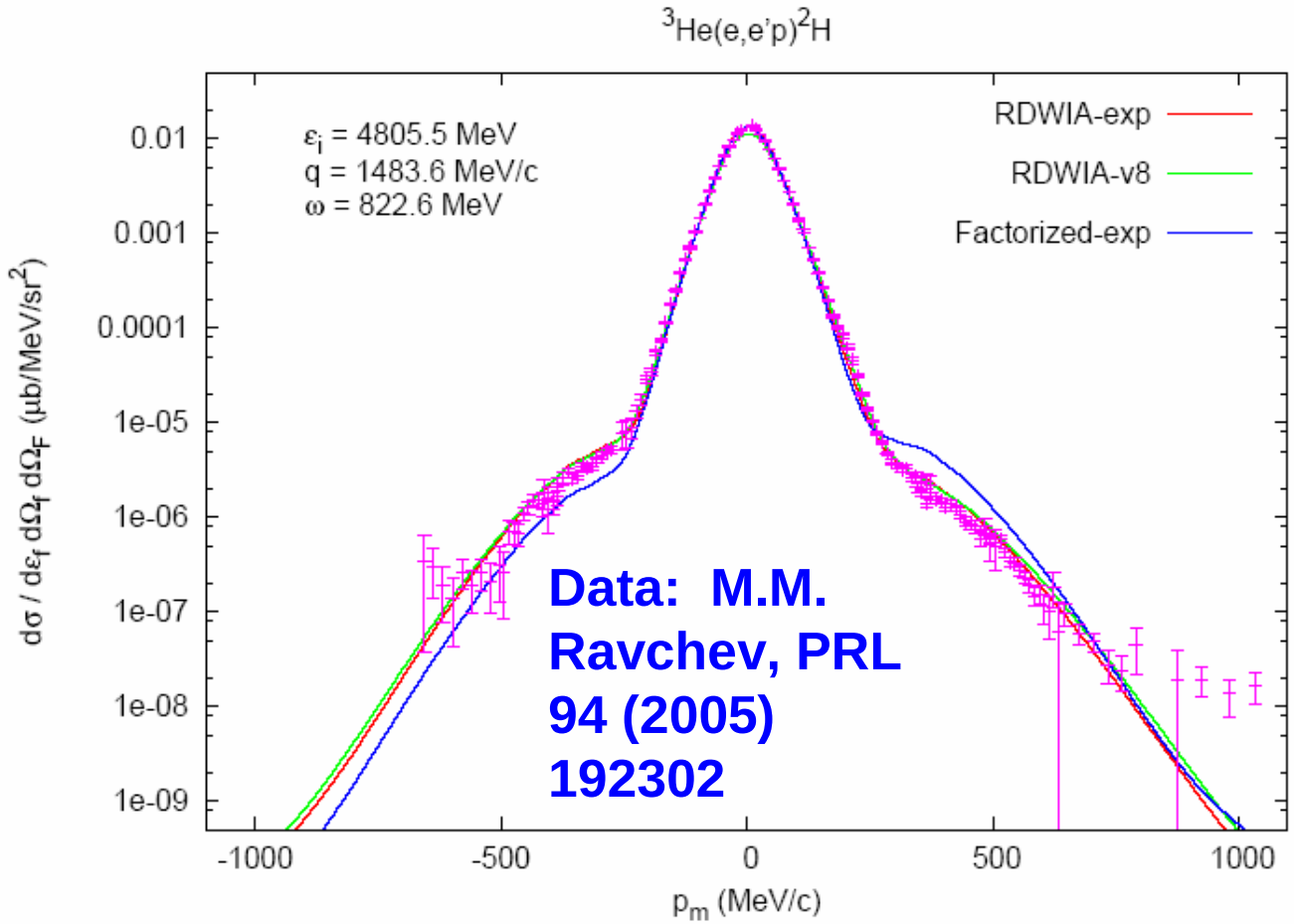


Breakdown of factorization will be seen at **demanding** kinematics (q-ω constant, high momentum)

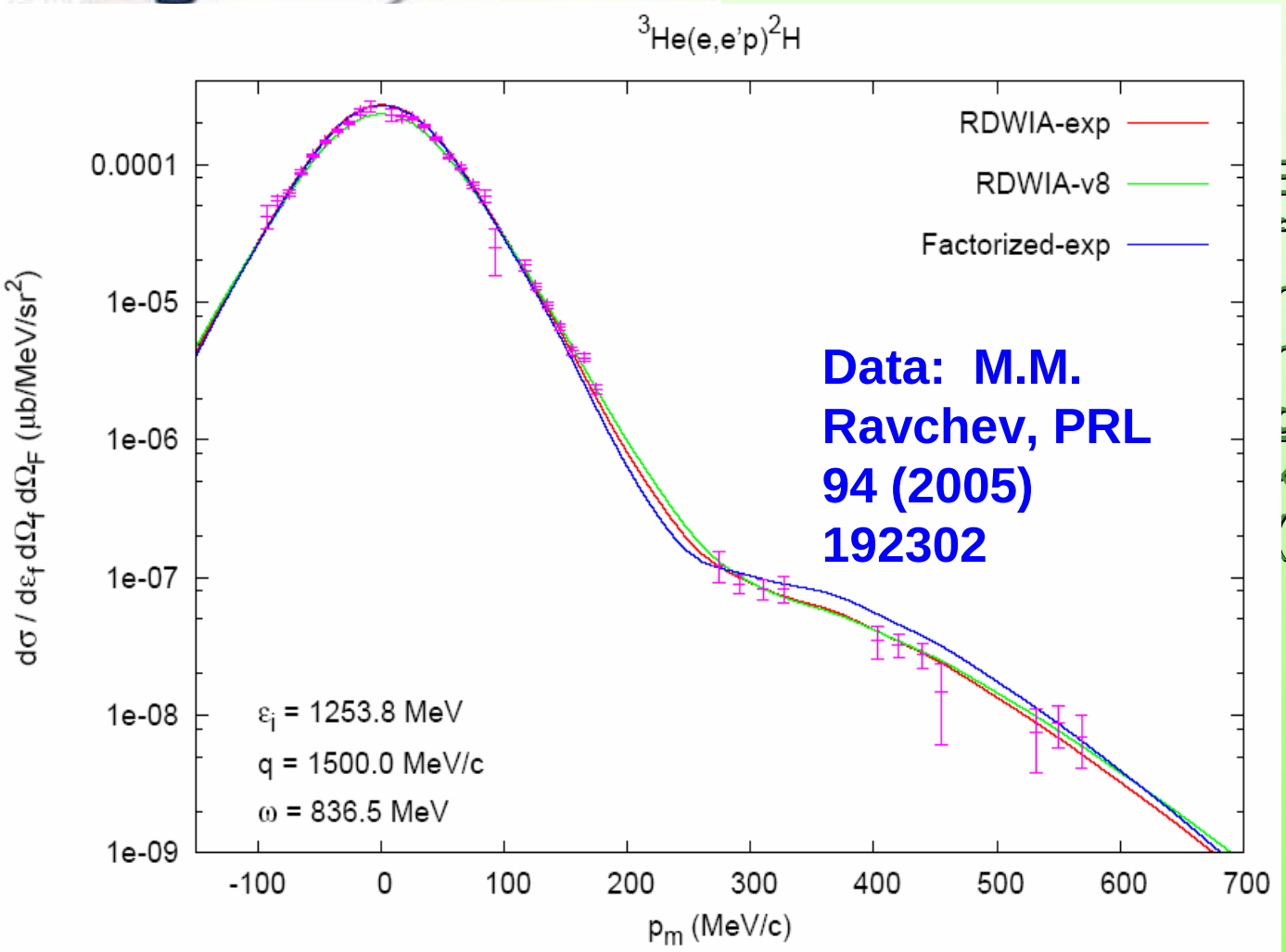


Data: M.M. Ravchev, PRL 94 (2005) 192302

Full theoretical calculation of the overlap from Faddev calculations. No free parameters in these results



Breakdown of factorization will be moderately seen at moderately demanding kinematics (moderately high p_m)



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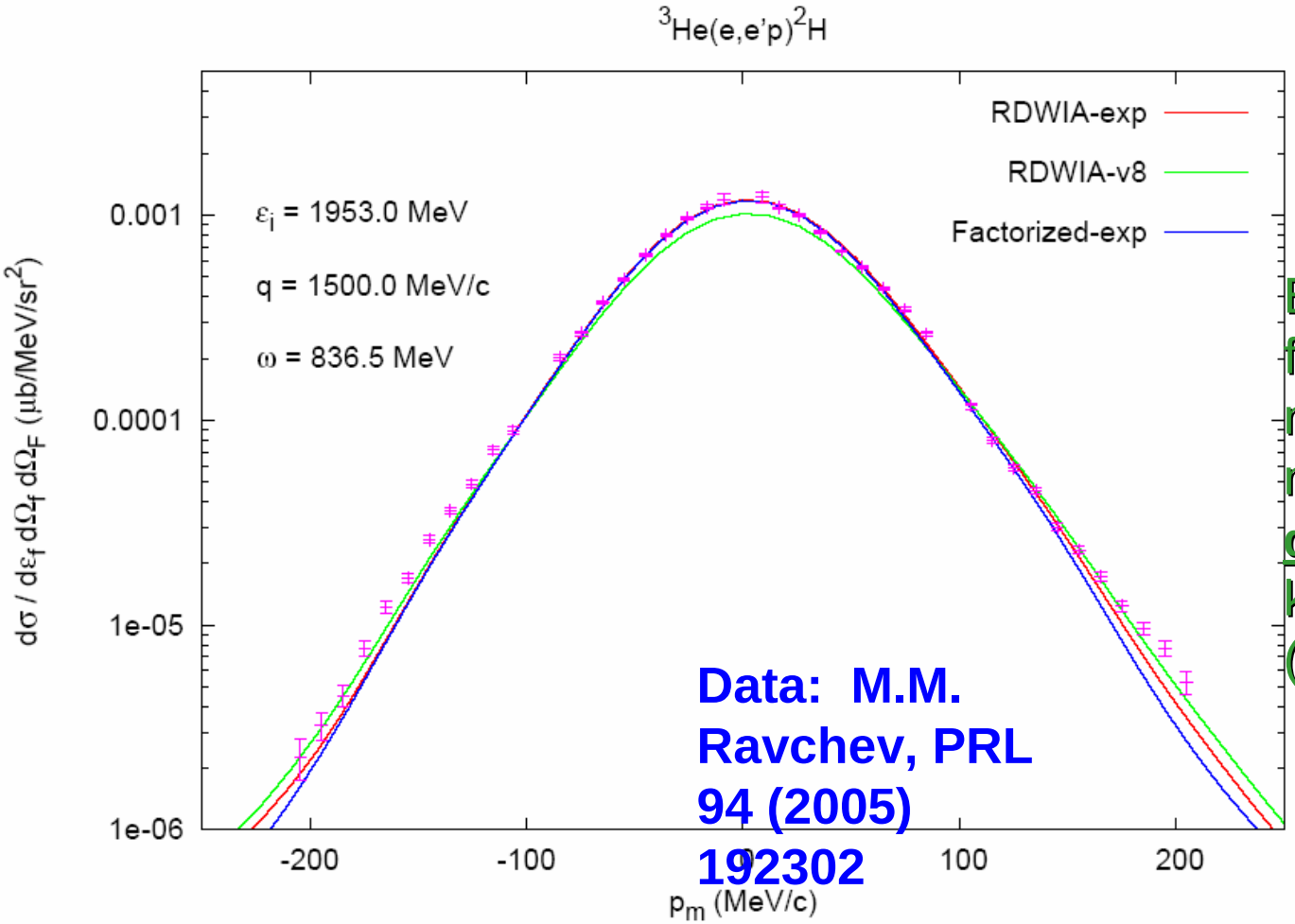


Data: M.M. Ravchev, PRL 94 (2005) 192302

Breakdown of factorization will be moderately seen at moderately **demanding** kinematics (moderately high p_m)

For inclusive scattering at QE kinematics and about-GeV energies

- Small breakdown of factorization in the cross-section
- The inclusive cross-section can be understood from the product of the nuclear response (spectral function) and the elementary probe-nucleon response
- To the extent that factorization is (aproximately) fulfilled, the elementary probe-nucleon response and kinematical factors are factored out and the remaining nuclear response is the same for same nucleus, q and ω transfer, irrespectively of the nature of the probe

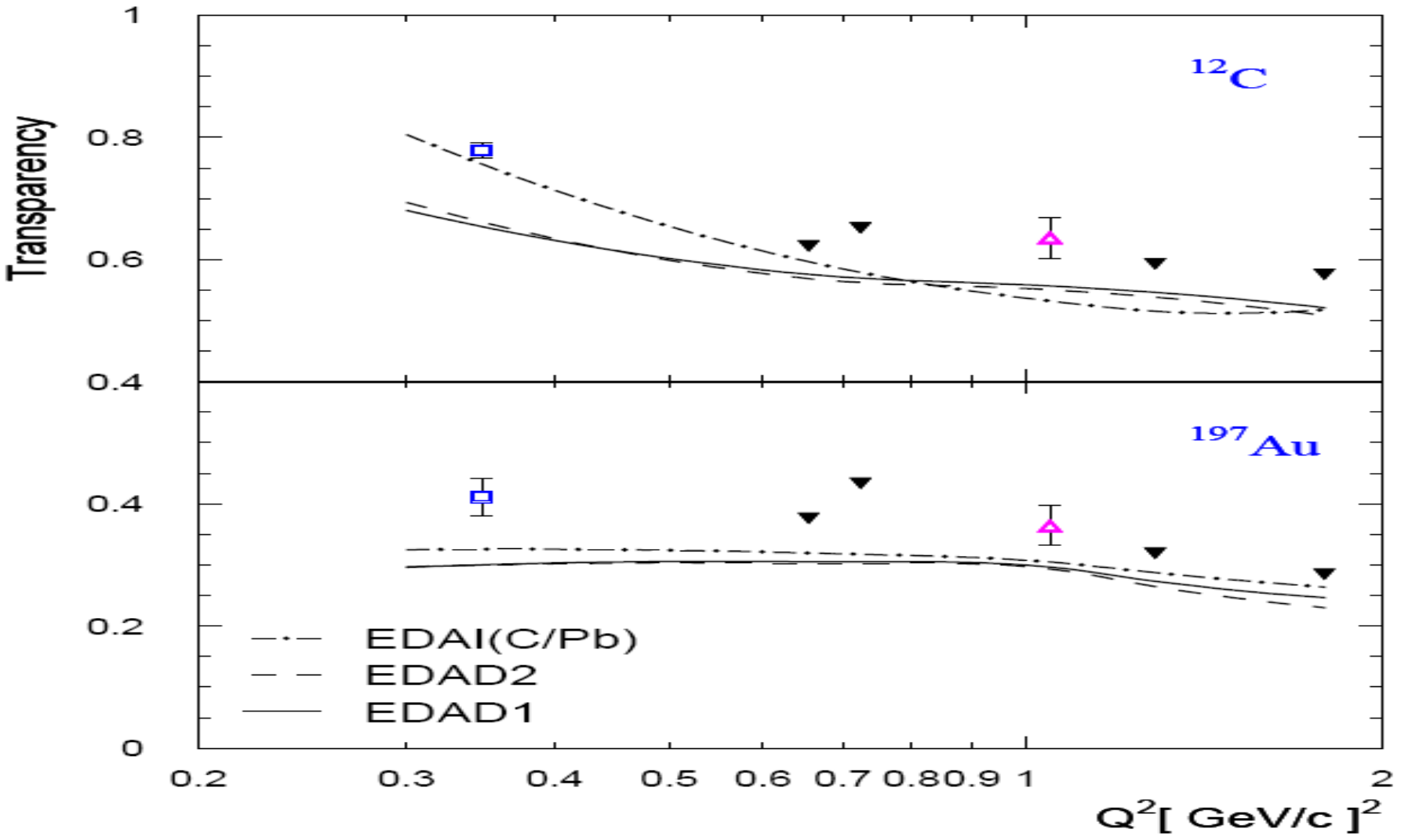
Transparency from (e,e'p)

$$T_{exp}(Q^2) = \frac{\int_{\Delta^3 p_m} d\vec{p}_m \int_{\Delta E_m} dE_m \; S_{exp}(\vec{p}_m, E_m, \vec{p}_F)}{c_A \int_{\Delta^3 p_m} d\vec{p}_m \int_{\Delta E_m} dE_m \; S_{PWIA}(\vec{p}_m, E_m)}$$

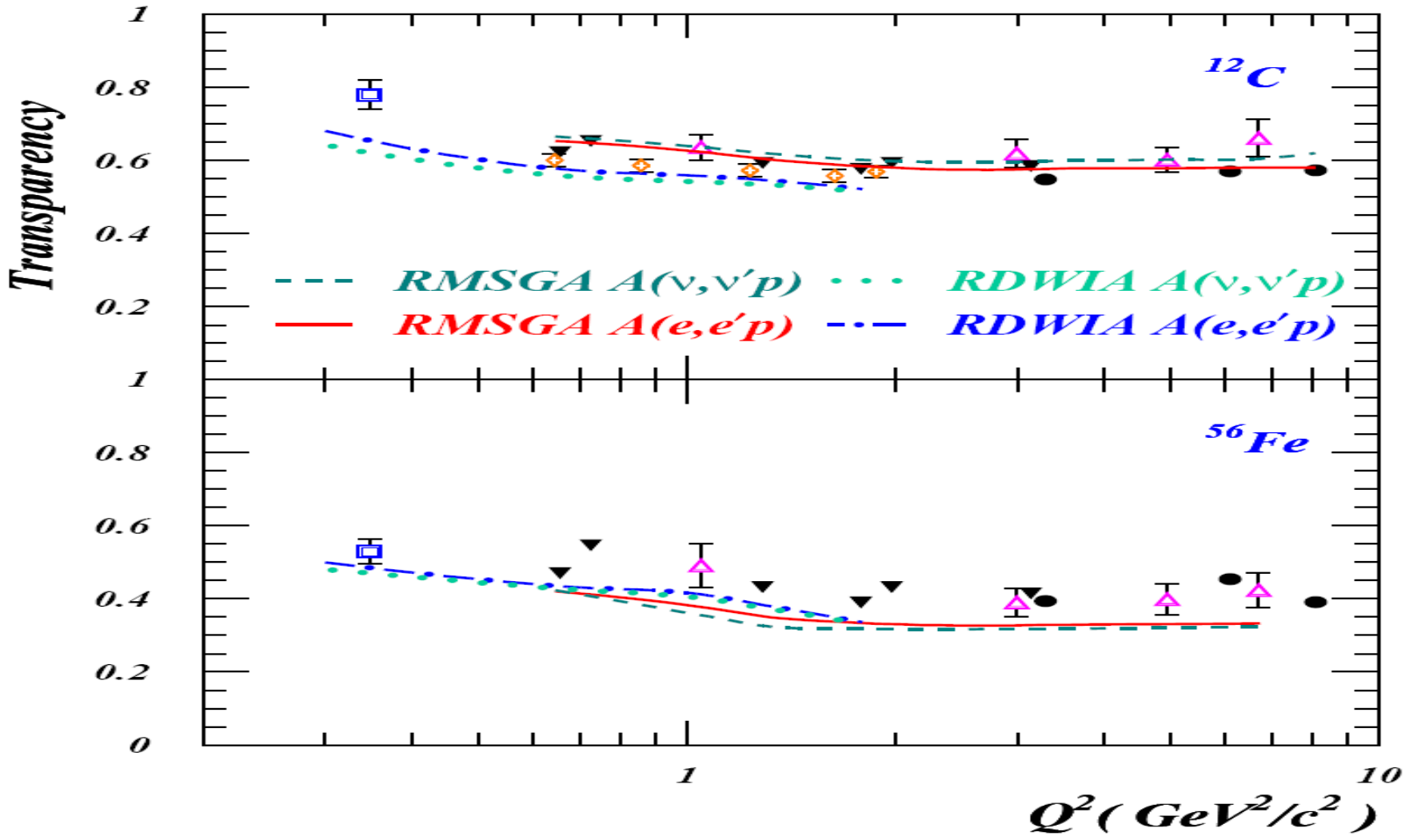
$$S_{exp}(\vec{p}_m, E_m, \vec{p}_F) = \frac{\frac{d^5\sigma^{exp}}{d\Omega_p d\epsilon' d\Omega_{\epsilon'}}(e, e'p)}{K\sigma_{ep}}$$

$$T_{theo}(Q^2) = \frac{\sum_\alpha \int_{\Delta^3 p_m} d\vec{p}_m S^\alpha(\vec{p}_m, E_m, \vec{p}_F)}{c_A \sum_\alpha \int_{\Delta^3 p_m} d\vec{p}_m S^\alpha_{PWIA}(\vec{p}_m, E_m)}$$

Comparison to data: too little transparency if using only elastic channel prediction



neutrino vs. electron transparencies



What do we observe?

- Transparencies are underpredicted by phenomenological optical potentials

- Glauber estimations are about right (^{12}C) or underpredict (for larger nuclei) the transparency

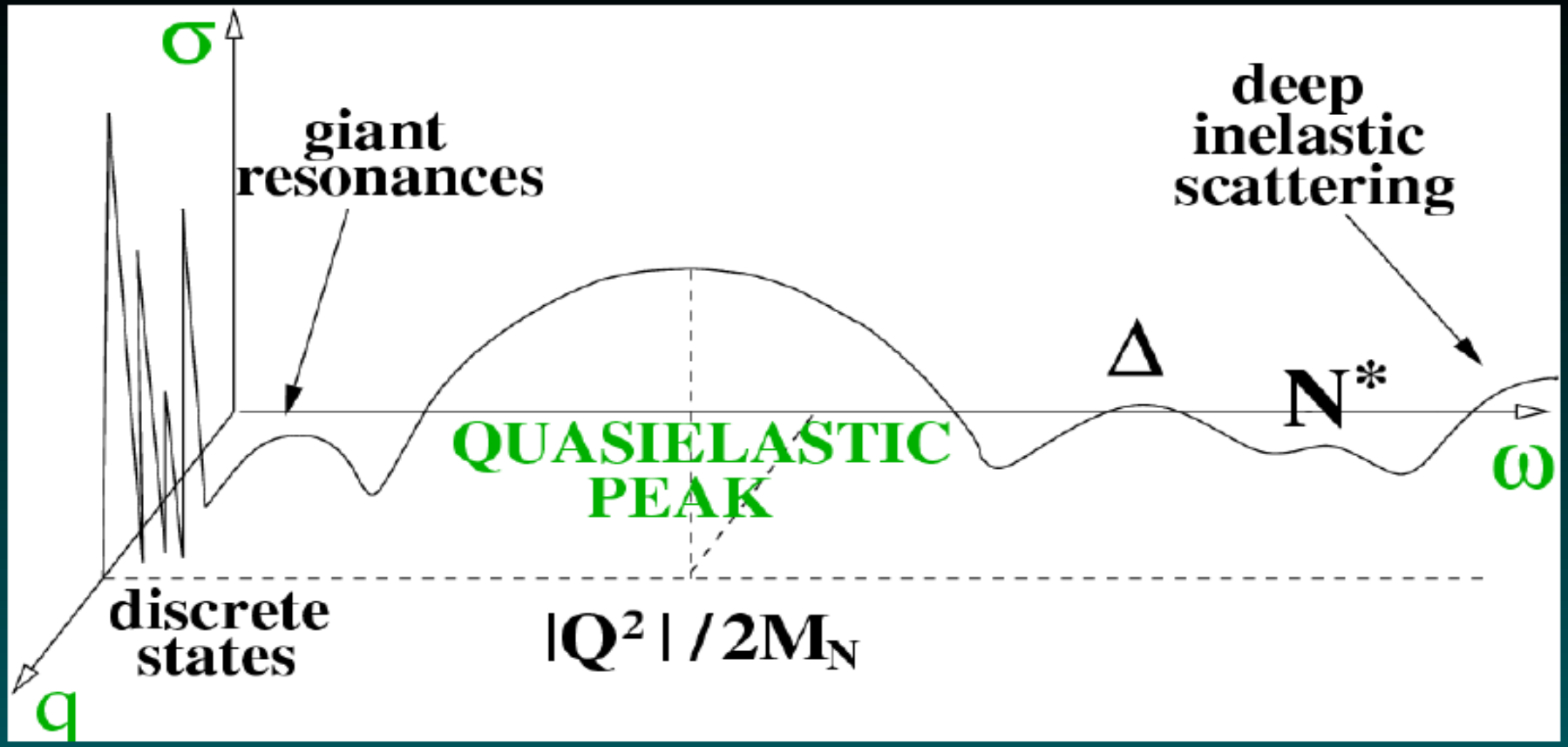
- The A-dependence is well described by the phenomenological optical potential

What do we conclude?

- Transparency (e,e'p) experiments, after all, are non-exclusive in a complicated and experiment-dependent way. They include more than just the elastic proton propagation channel
- Optical potential results ***represent just an absolute lower bound to the transparencies***

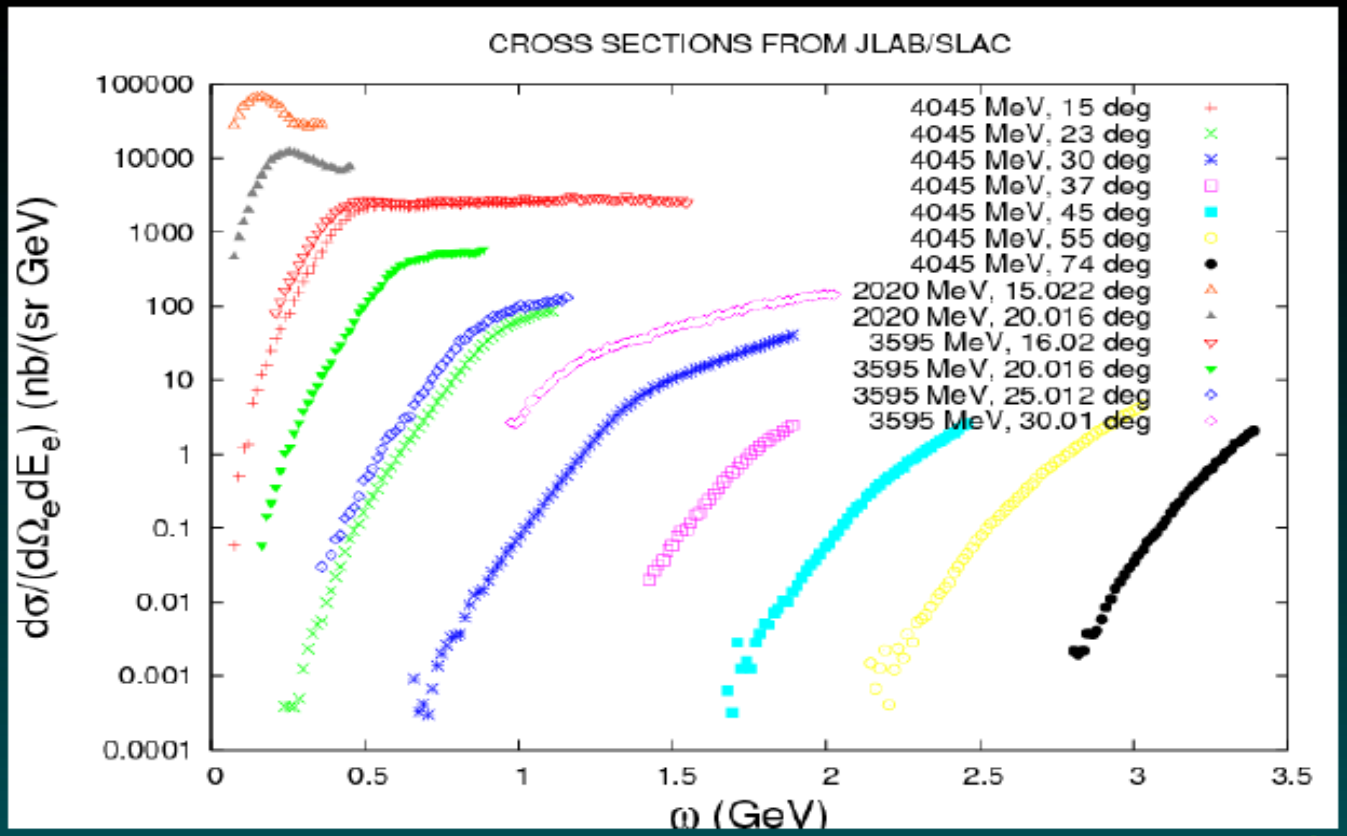
- What can we learn from **inclusive** experiments?

Inclusive electron scattering on nuclei



Many things may happen to the nucleus, depending on the values of q and ω

Inclusive ^{12}C quasielastic electron data



Day *et al*, PRC48(1993)1849

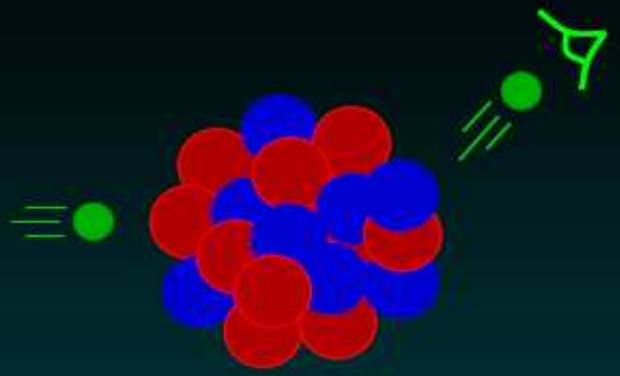
Arrington *et al*, PRL82(1999)2056

$0.5 < q < 4$ GeV/c

$$f(q,\omega) \propto \frac{\left[\frac{d\sigma}{d\Omega_e dE_e}\right]}{\overline{\sigma}_{electron-nucleon}}$$

Can we organize *inclusive* nuclear cross-section data?

Some general ideas about scaling in inclusive scattering



- Requires a **weakly interacting probe** and a **composite target**
- The probe must scatter from **one of the bound constituents** of the target

$$F(q,\omega) = \frac{\left[\dfrac{d\sigma}{d\Omega_{probe} dE_{probe}}\right]}{\overline{\sigma}_{probe-constituent}}$$

At high q this function depends on a combination of q and $\omega \Rightarrow$ **SCALING**

y-scaling variable?

y is the minimum initial momentum of the nucleon allowed by the kinematics.

$$y \approx \sqrt{\omega(2M_N + \omega)} - q$$

$$\text{If } y = 0 \Rightarrow$$

$$q^2 = \omega(2M_N + \omega) \Rightarrow$$

$$|Q^2| = 2M\omega$$

y and Bjorken x scaling variables are closely related to each other! One has binding energy and nucleus recoil corrections

We will use $\psi = y/k_F$ as scaling variable

Scaling: An important simplification (I)

- If we were dealing with scattering off free nucleons, the nuclear response would not depend on q and ω in an independent fashion, rather it would depend only on Q^2 (or any function of Q^2)

- As the nucleons in the nucleus are bound and strongly interacting (i.e., they are off mass-shell), a certain dependence on both q and ω and not only Q^2,may be expected. This extended dependence can be also due to FSI

Scaling: an important simplification (II)

•Most models that deal with nucleons are barely off-shell (if at all) and either they have no FSI, like the Fermi Gas (relativistic or not) or they have relatively weak FSI, as most nonrelativistic models. They do not display significant dependences on the scaled response other than Q^2. It is not surprising that these models exhibit *scaling of first kind*

•The variability in the nuclear species, once factored out the single-proton and single-neutron response, can be described by only one parameter, the Fermi momentum. As this density dependence can be factored out very effectively in most models, all nuclei display the same k_F-scaled 'nuclear' response. This is *scaling of second kind*

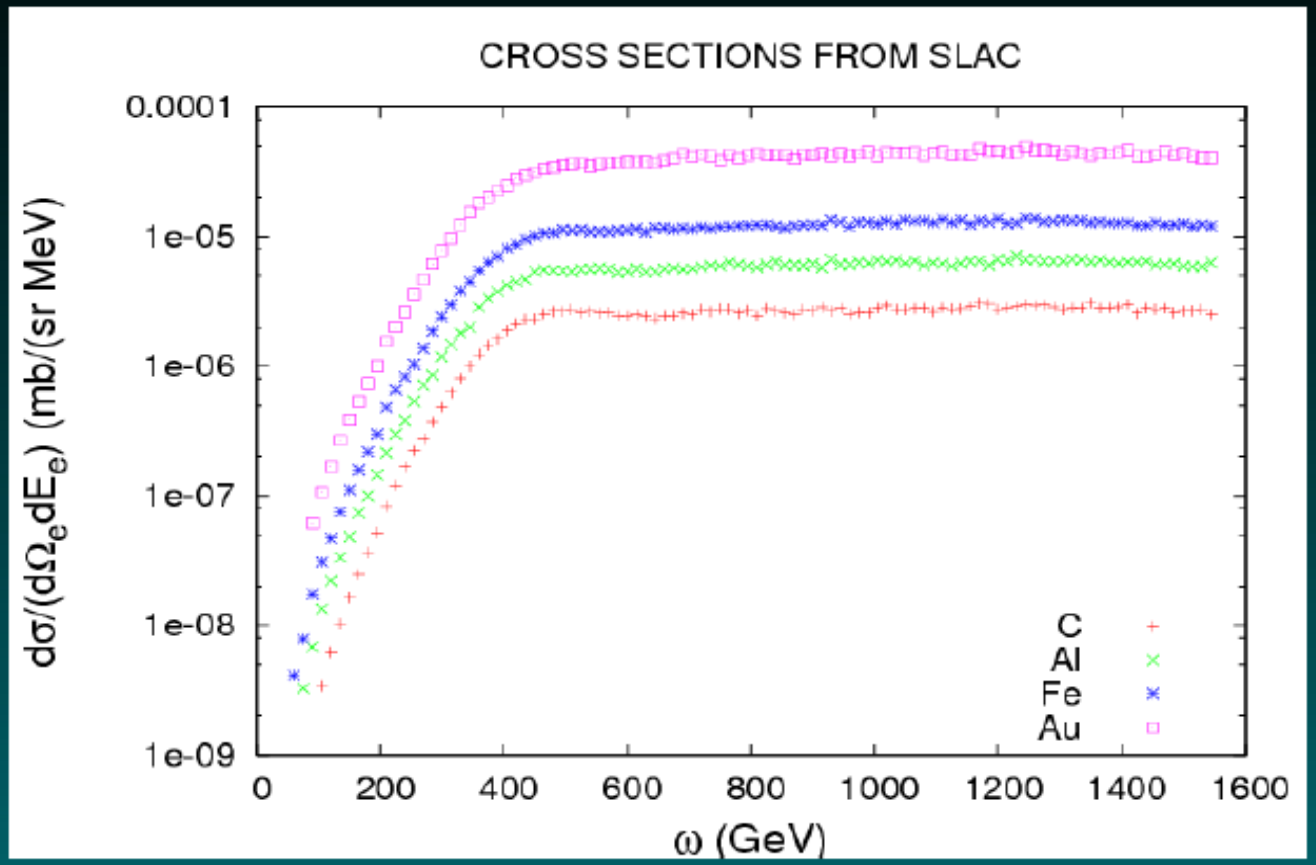
For inclusive scattering at QE kinematics and GeV energies

- Factorization is a pre-requisite for scaling that is not strictly fulfilled if strong potentials are present, due to the enhancement of the lower components, dispersive effects and LS terms but, in fact, the factorization approach works quite well for cross-sections under QE conditions, OBE and IA, even for a model like RMF

Per nucleon response is almost constant

More inclusive quasielastic electron data

Same transferred momenta,
different targets (C, Al, Fe, Au)

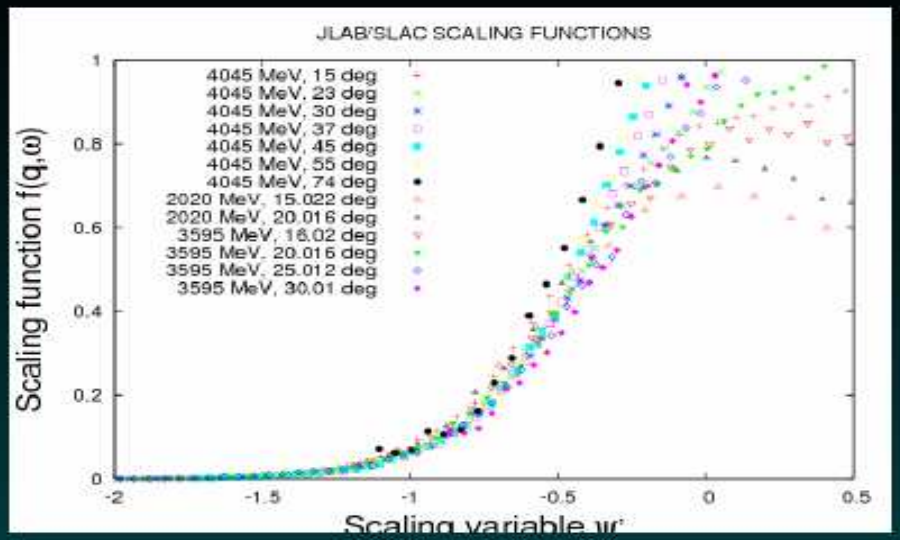


Day *et al*, PRC48(1993)1849

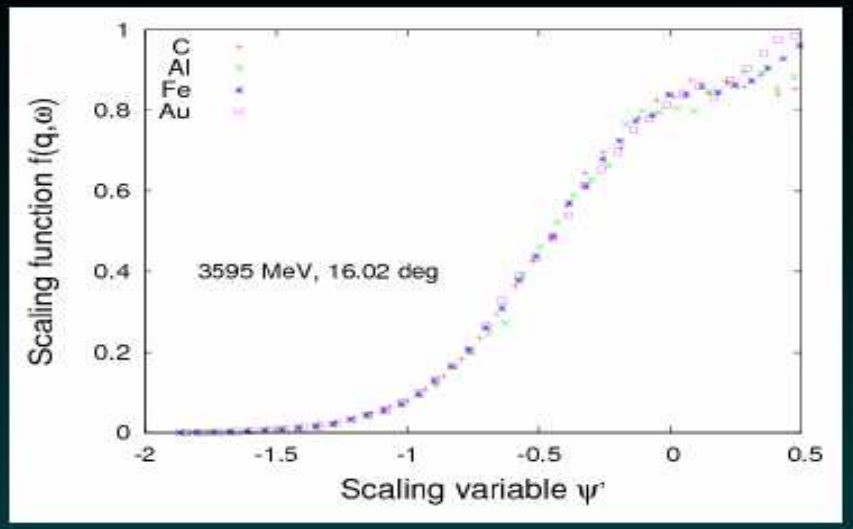
$q \approx 1$ GeV/c
$E_e = 3{,}6$ GeV,
$\theta_e = 16^o$

As a summary

Same target (^{12}C), different transferred momenta



Same transferred momenta, different targets (C, Al, Fe, Au)



FIRST KIND SCALING

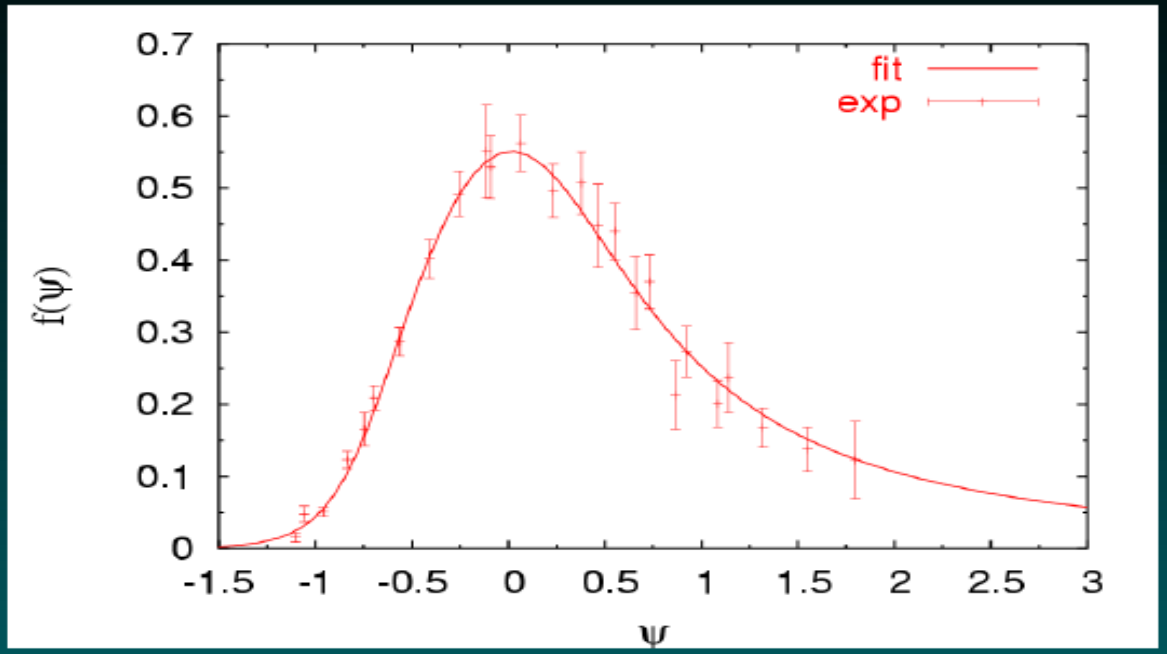
SECOND KIND SCALING

FIRST (y-scaling) + SECOND = SUPERSCALING

Day *et al*, Ann. Rev. Nucl. Part. Sci. **40** (1990) 357,
Donnelly and Sick, Phys. Rev. C **60** (1999) 065502,
Donnelly and Sick, Phys. Rev. Lett. **82** (1999) 3212

Inclusive electron data exhibit superscaling behaviour in the QE (and also in the Δ peak) region

$\Rightarrow$ **we have a phenomenological scaling function**



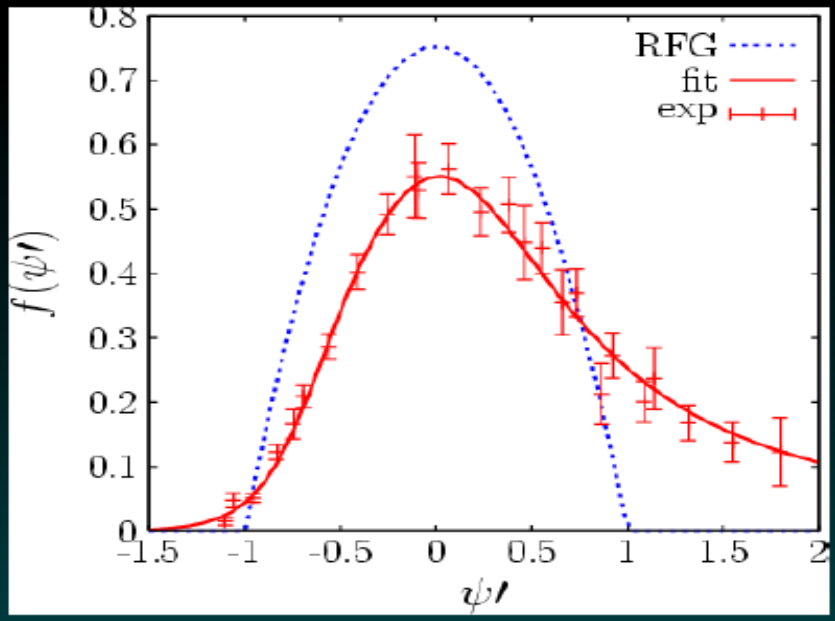
(e, e') **DATA** $\Longleftrightarrow$ **SCALING FUNCTION**

Relativistic Fermi Gas:

Perfect superscaling behaviour
(Alberico *et al*,
Phys. Rev. C 38, 1801 (1988))

Experimental data:

Good superscaling behaviour, although not perfect



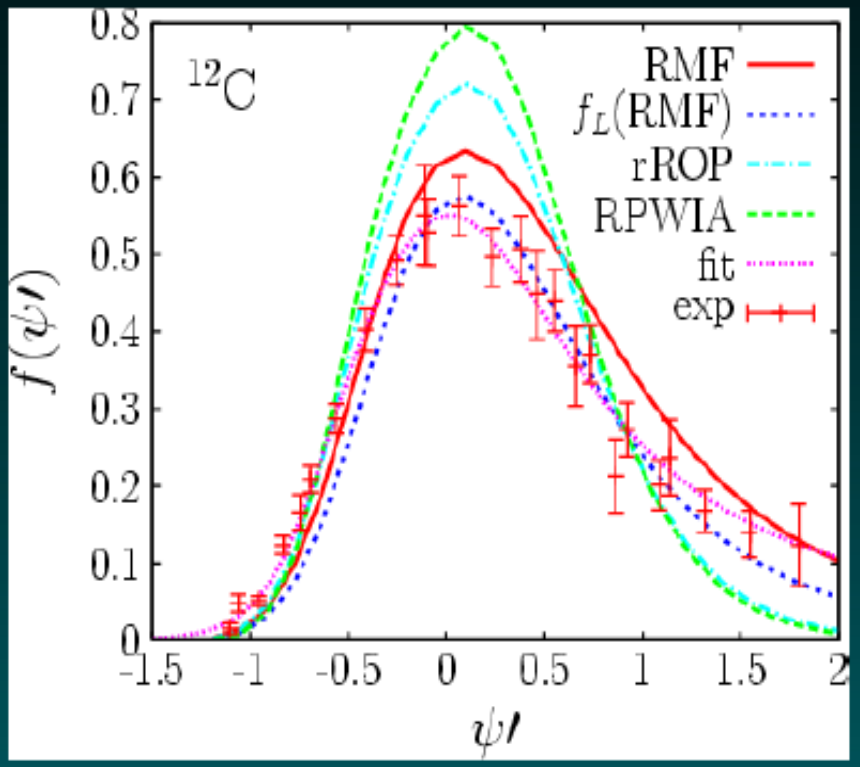
The RFG superscales, and data also superscale, but the scaling functions of data and of RFG disagree ⇒

The RFG lacks important initial and final state nuclear dynamics effects, even at high energies!

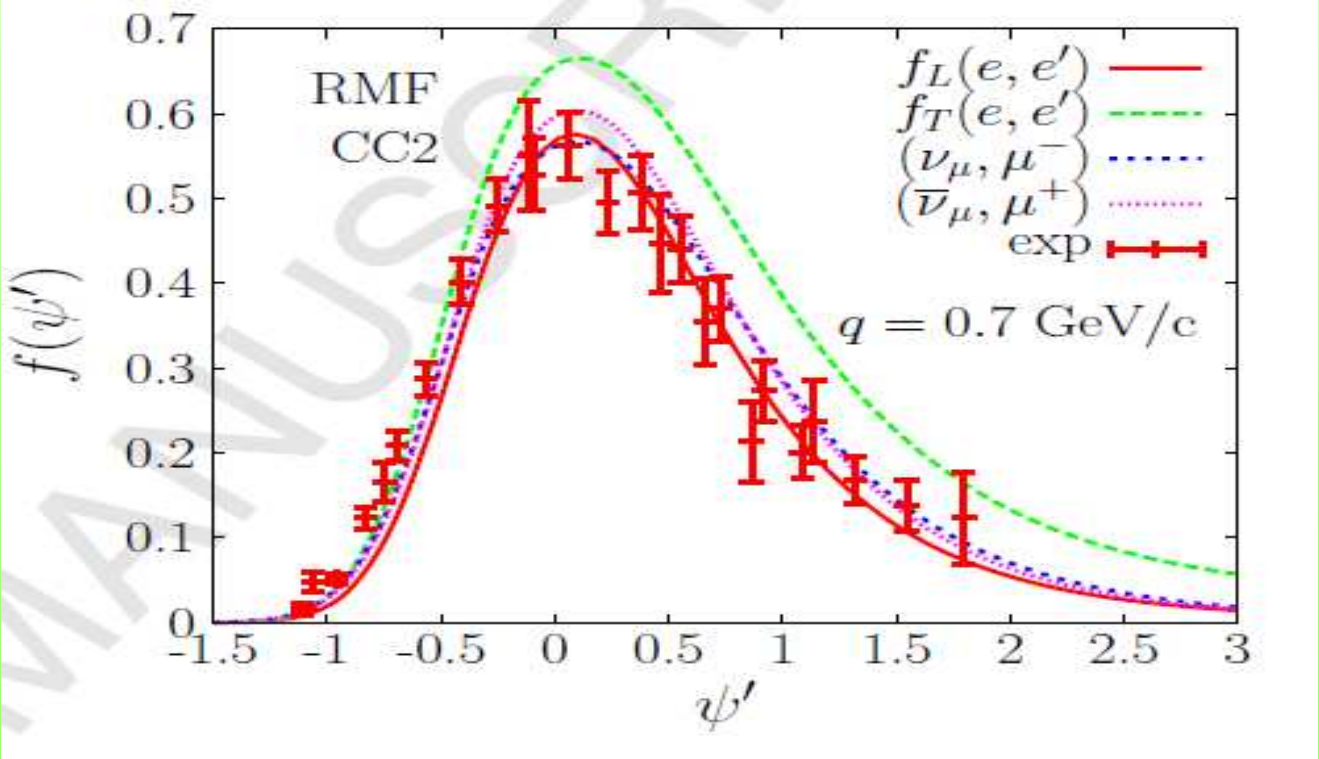
...not many models have been able to reproduce the experimental scaling function...

The **RELATIVISTIC IMPULSE APPROXIMATION + RELATIVISTIC MEAN FIELD (RIA-RMF)** for describing the bound and ejected nucleon does, both in magnitude and shape

(Caballero et al,
Phys. Rev. Lett. **95**, 252502 (2005),
Phys. Rev. C **74**, 015502 (2006)...)

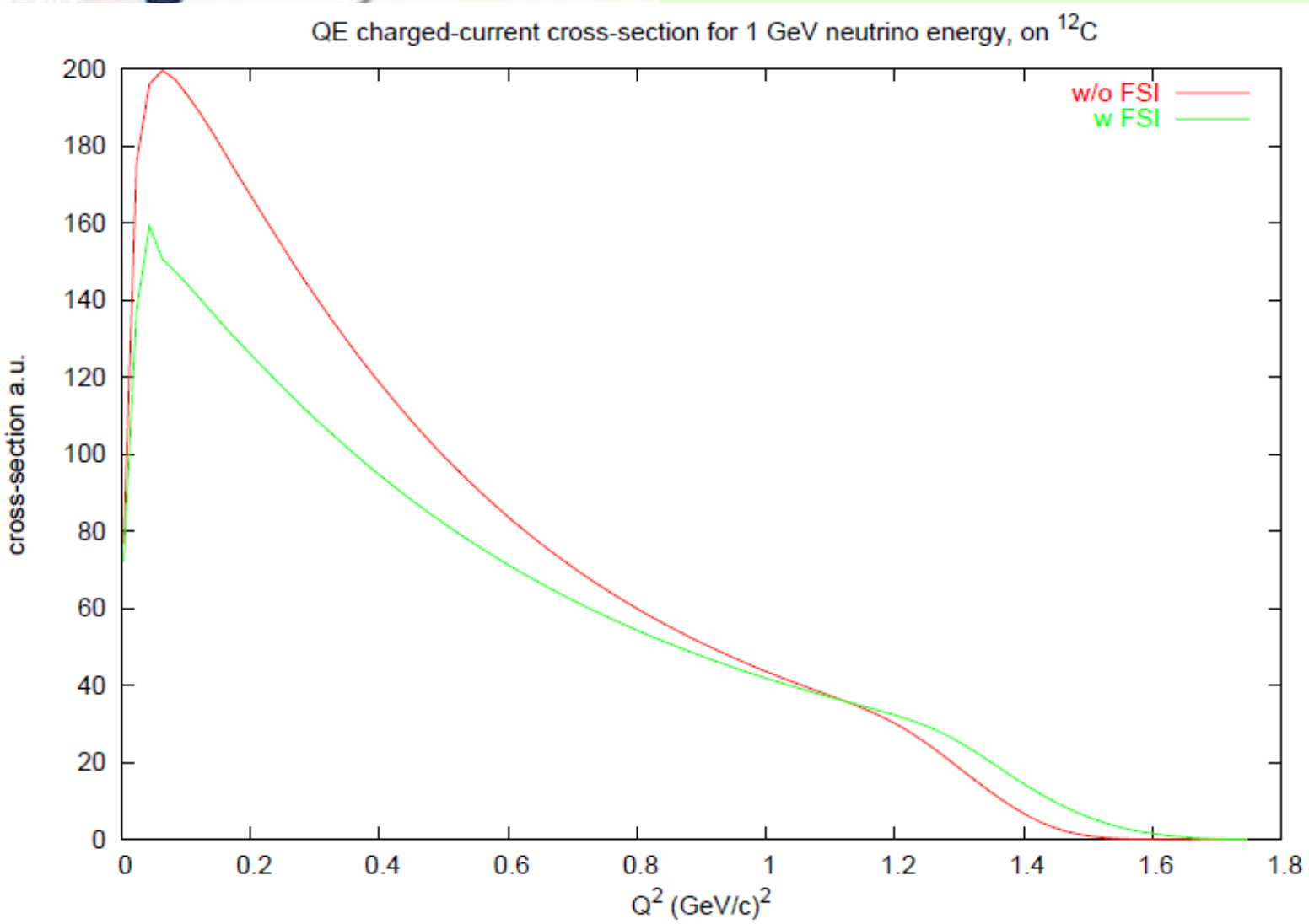


The theoretical analysis indicates that the universal superscaling function is, to a very large extent, independent on the probe. This comes from actual calculations for electron, charged and neutral currents within RMF model. Scaling of *THIRD* kind?



Use scaling to predict neutrino-nucleus cross-section. It's easy for charged currents

For neutral ones?



RMF calculations show that FSI have an effect even for 1 GeV neutrino energy

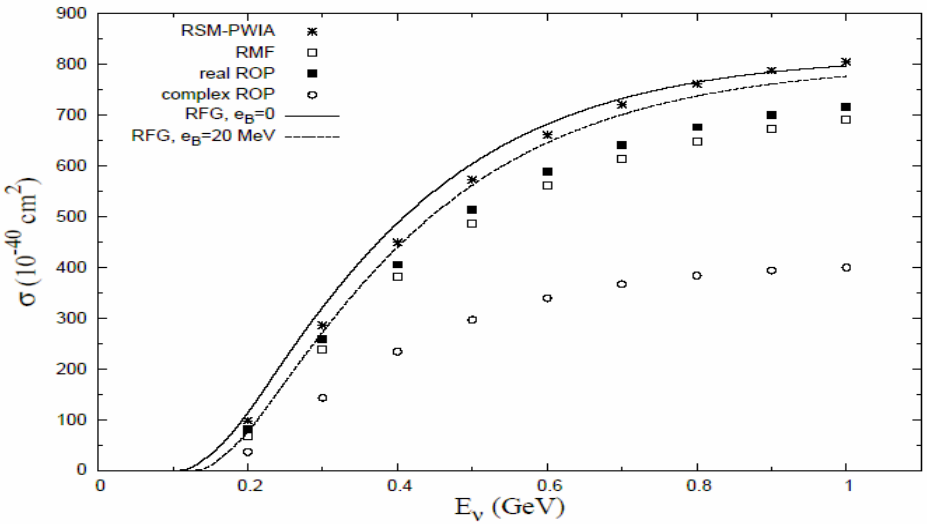


FIG. 4: Integrated cross section $\sigma(E_\nu)$ for the quasielastic scattering of muon neutrinos on ^{16}O as a function of the incident neutrino energy. The curves are calculated within the RFG model with $k_F = 225$ MeV and binding energy $e_B = 0$ (solid line) and $e_B = 20$ MeV (dashed). The points correspond to RSM calculations without FSI (stars) and with FSI effects taken into account within the RMF (empty squares), real ROP (full squares) and complex ROP (circles) approaches.

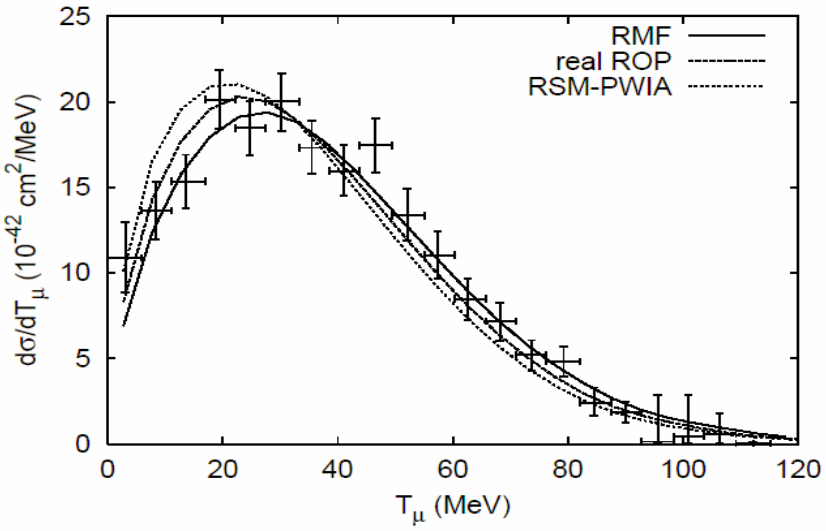


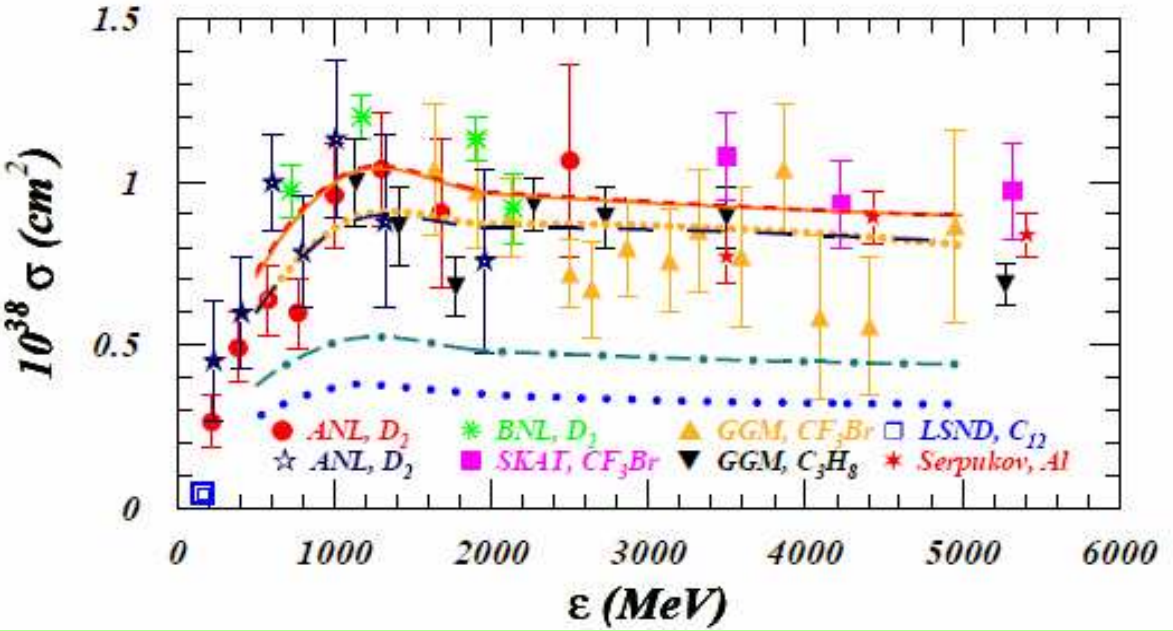
FIG. 5: Observed distribution of muon kinetic energies T_μ compared with the flux–averaged predictions of our RSM, in PWIA (dotted line) and including FSI within the RMF (solid) and purely real ROP (dashed) frameworks. The theoretical distributions have been normalized to give the same integrated values as the experimental points, and have been folded in energy with a bin size of 5 MeV, the same employed for the experimental data. Data are from Albert et al. [12].

Comparison to LSND $^{12}C(\nu,\mu^-)X$ data

σ_{RMF}=(15 to 16) x 10^{-40} cm^2 that is 40% above data. MEC shall reduce this by no more than 10%

Y. Umino et al. PRC 52 (1995) 3399

RMF predictions for nucleonic contributions to CC and NC neutrino scattering can be done



Total CC predictions for non-pionic 'quasielastic' charged current reactions (ν,μ^-) obtained: a) without FSI interactions (red curve). With FSI interactions within RMF for ^{12}C and ^{56}Fe (dotted orange and long dashed blue lines, respectively). 'Pure' elastic contribution is shown by dot-dashed (green, ^{12}C) and long dotted (cyan, ^{56}Fe) curves. Data from several experiments and targets are also plotted. 10% effect of FSI can be observed, even at 5 GeV

M.C. Martínez et al., PRC73 (2006) 024607

Procedure to check validity (or not) from scaling:

1. Get our inclusive NC neutrino-nucleus cross sections ($d\sigma/dE_N d\Omega_N$) by integrating over the scattered neutrino variables our exclusive cross sections.

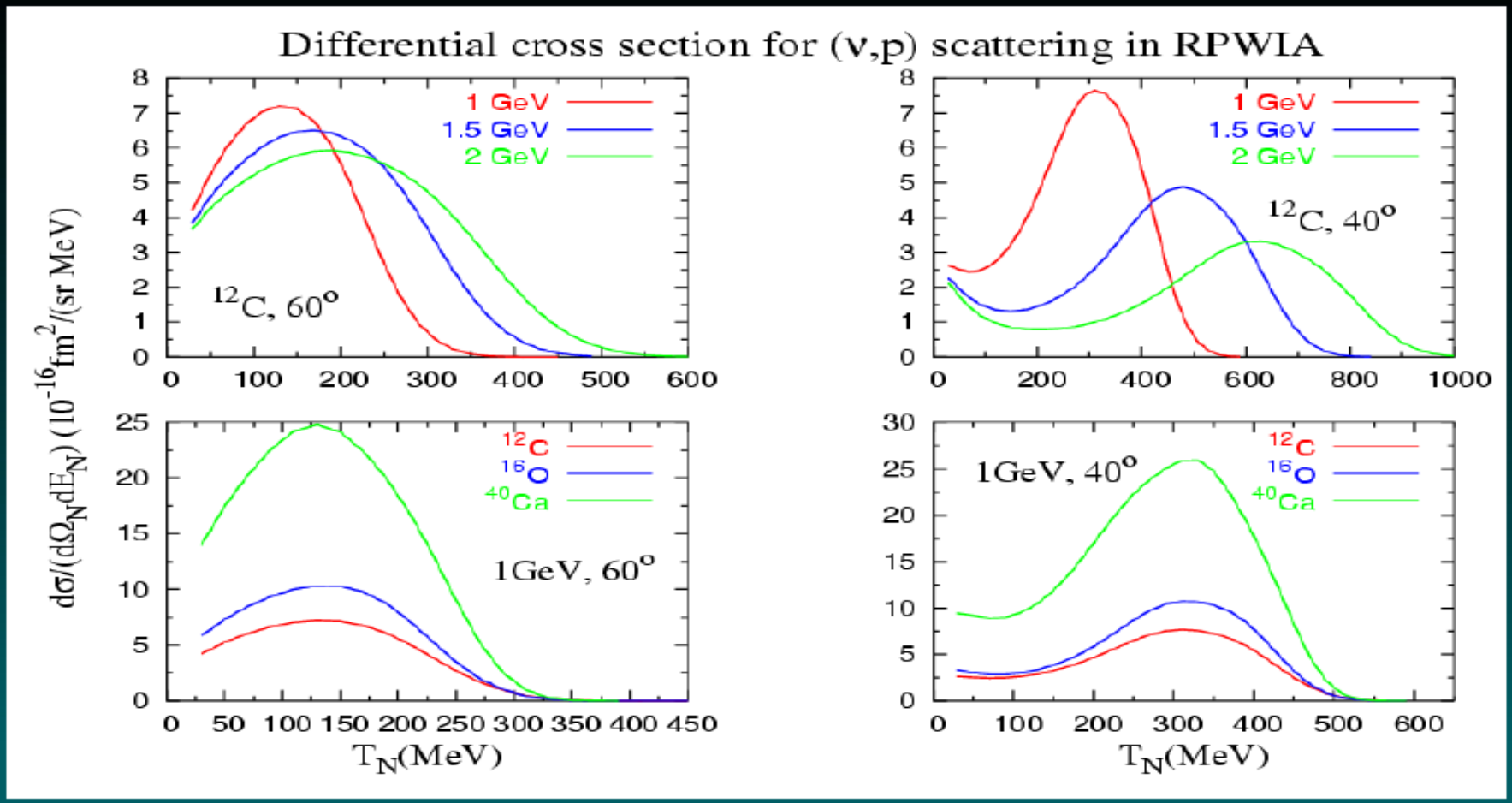
2. Divide by an averaged (over ϕ') NC neutrino-nucleon cross section. Multiply by the Fermi momentum k_F of the nucleus to make the result adimensional in order to check scaling of first and second kind.

$$f(q', \Psi') = k_F \frac{\left[\frac{d\sigma}{d\Omega_N dE_N}\right]}{\overline{\sigma}_{sn}^{NC}}$$

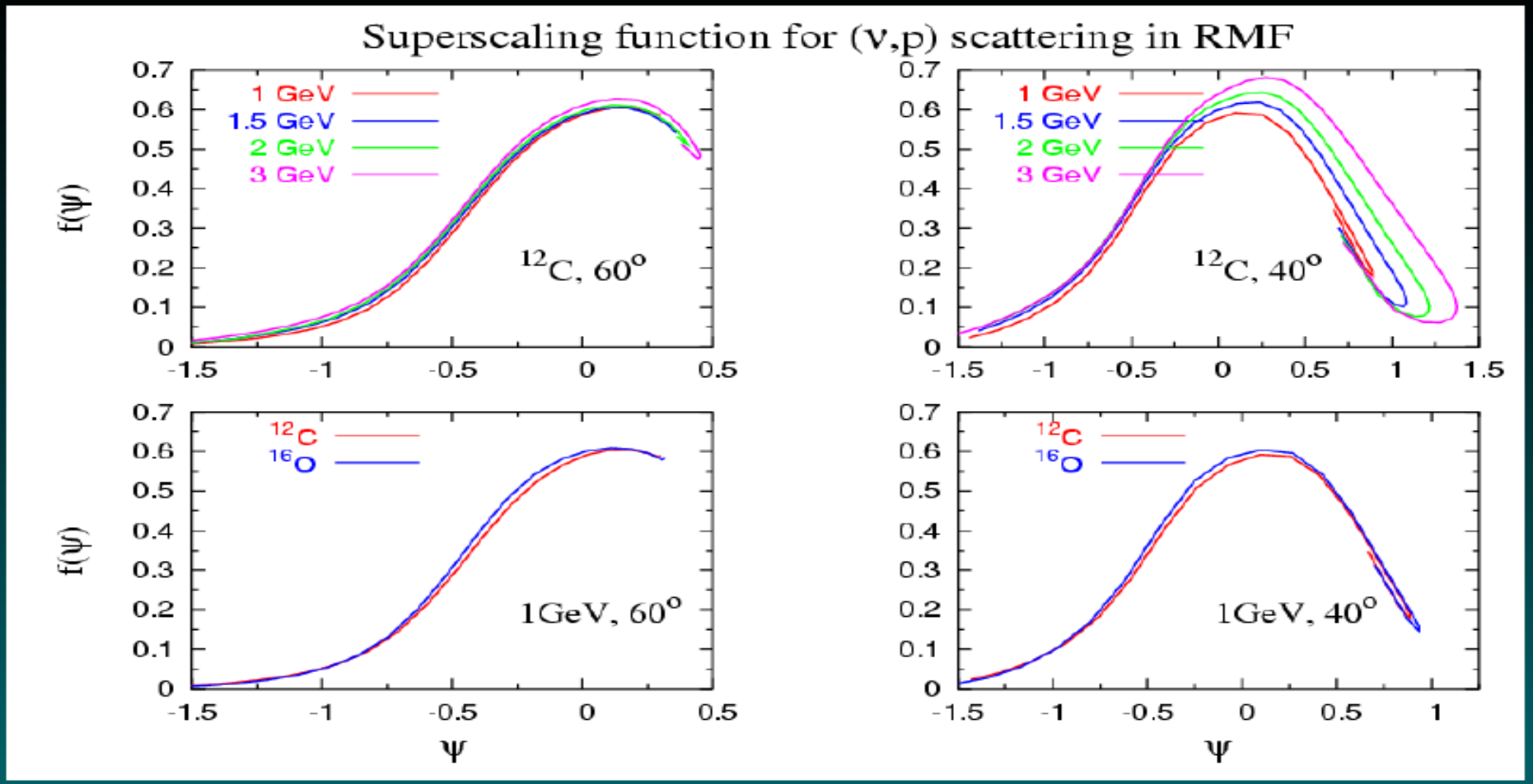
3. Represent the result as a function of a NC scaling variable Ψ', derived in Phys. Rev. **C** 73, 035503 (2006), inspired in the RFG.

Note: All the responses (L, T, TL, TT, T', TT') will contribute to our u-inclusive cross section!

Results: Cross sections for different beam energies and nuclei for neutrinos



Results: Superscaling within RMF



CONCLUSIONS

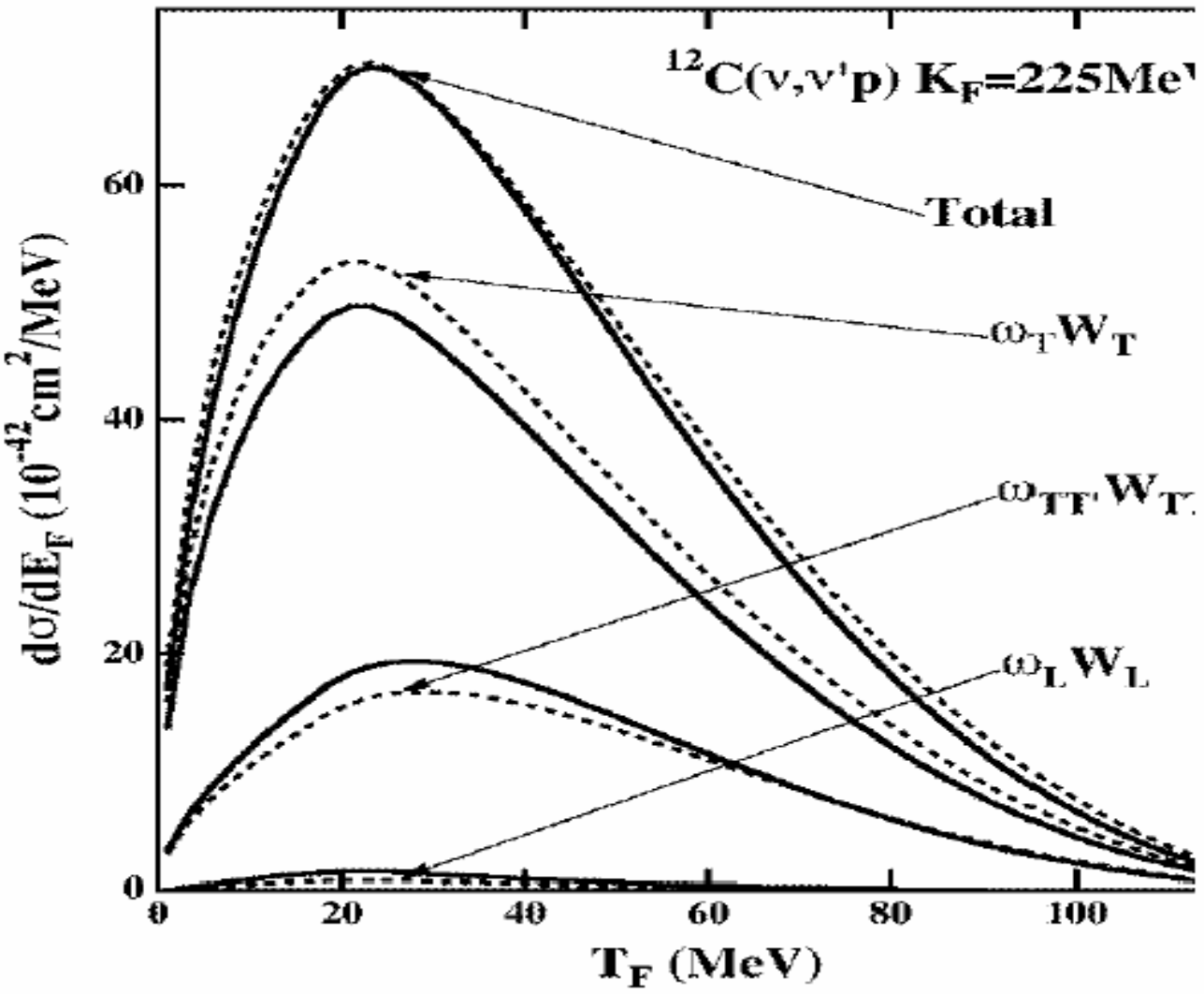
•RMF (and from why I've seen Ankowsky-spectral function based results and GiBUU predictions on the lepton side) agrees well with the scaling function, where scaling applies. RMF is not as limited to high momentum transfer as scaling approaches

•RMF exhibits scaling (and slight departure from it) of first and second kind (and also zero kind) at a level similar to the one allowed by the data. Further extensive comparisons of RMF to available electron scattering data show good agreement for the pure nucleonic responde in the 0.3-2.5 GeV/c q range

•RMF, ins spite of off-shell nucleons and strong FSI, shows good scaling of third kind, that is, universality of nucleonic response to weak interaction probes

•For the neutral current case with u-channel kinematics, scaling is a good approximation for not too small (>60º) nucleon scattering angles

•If or when scaling (response depends on one variable) fails, factorization can be employed to predict neutrino cross-sections from electron scattering data by means of extraction of a distorted spectral function (depends on two variables)

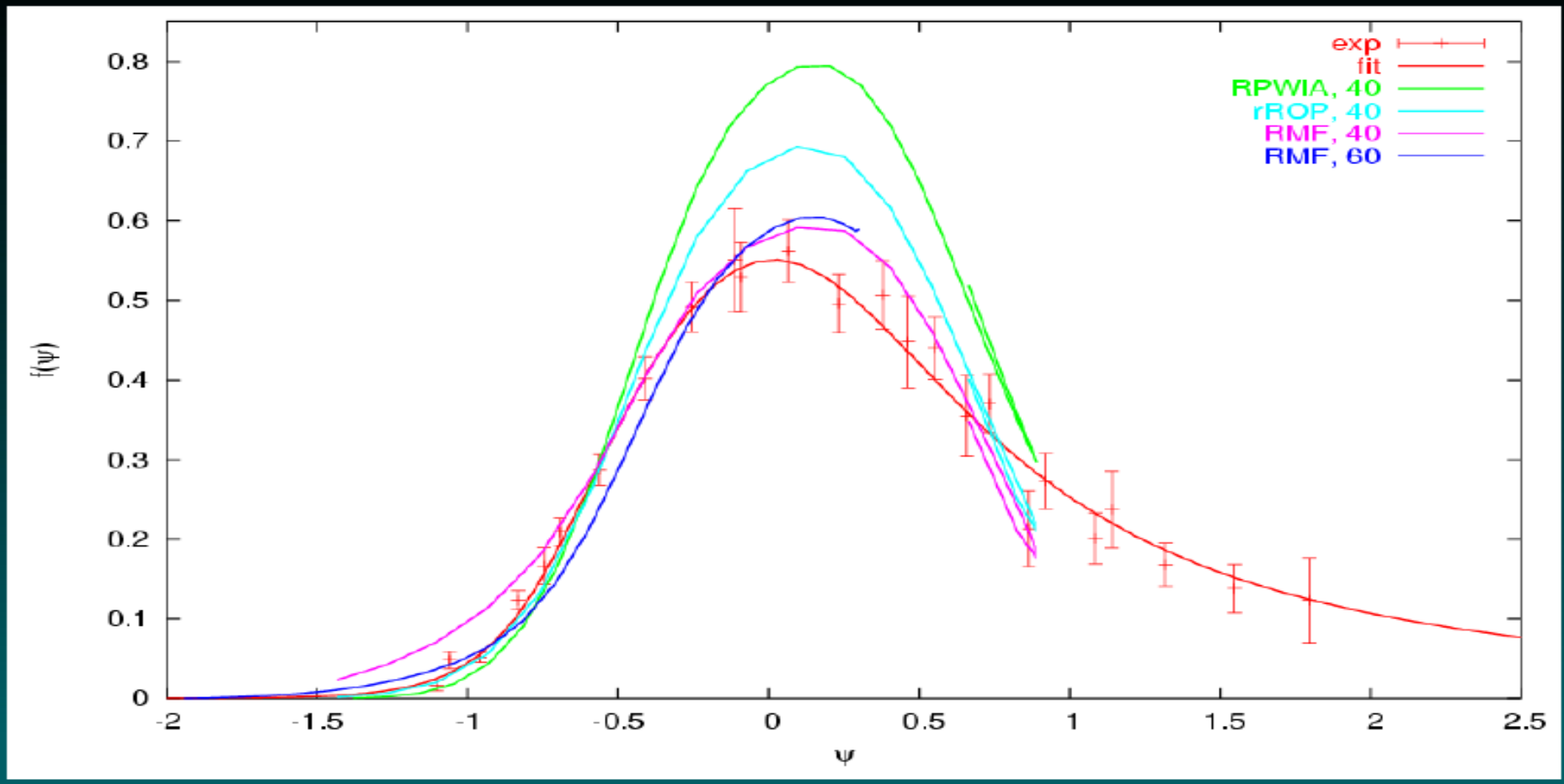

$^{12}C(\nu,\nu'p)$ K_F=225Me
Total
$\omega_T W_T$
$\omega_{TT'} W_{T'}$
$\omega_L W_L$
$d\sigma/dE_F$ (10^{-42} cm^2/MeV)
T_F (MeV)
0
20
40
60
80
100

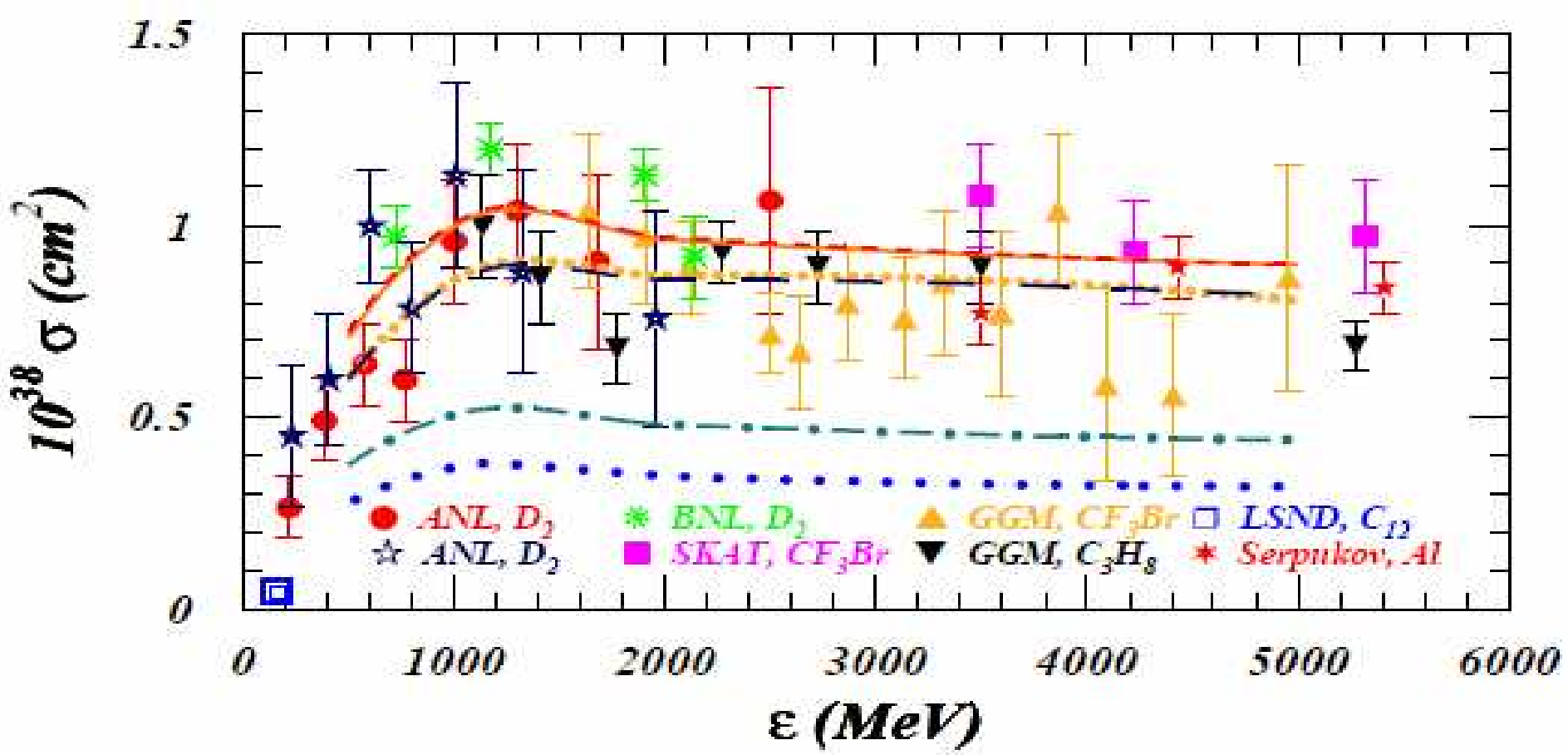
First issue we want to address:

Does the Relativistic Impulse Approximation (RIA) provide superscaling for NC neutrino-nucleus reactions?

- RIA has been extensively and successfully applied in investigations of **exclusive electron scattering reactions.**
- RIA has been shown to superscale for **QE inclusive electron and CC neutrino scattering.**
- RIA+RMF reproduces adequately the **asymmetric tail** exhibited by the experimental scaling function

Comparison to (e, e') averaged experimental function





Total CC predictions for **'quasielastic' charged current reactions** (ν,μ^-) obtained: a) without FSI interactions (red curve). Within RMF modeling for ^{12}C and ^{56}Fe (dotted orange and long dashed blue lines, respectively). 'Pure' elastic contribution is shown by dot-dashed (green, ^{12}C) and long dotted (cyan, ^{56}Fe) curves. Data from several experiments and targets are also plotted. 10% nuclear effects in the RMF can be observed, even at 5 GeV

M.C. Martínez et al., PRC73 (2006) 024607

Summary

(1) Electron scattering data show good scaling properties, allowing for the definition of a model independent universal nuclear response that can be employed to predict neutrino cross-sections

(2) The RMF is successful in describing inclusive (e,e') data and the universal scaling function. Under RMF, the same scaling function applies to electron, neutral and charged current scattering

(3) Neutrino CC fully inclusive QE data show saturation at large energies and a cross-section per nucleon that is A-independent, indicating a closure effect

(4) The A-dependence of transparencies appears because they are not fully inclusive experiments. Optical potential predictions are just a lower bound for transparencies, saturated only if they corresponded to fully exclusive measurements (with full occupancies). RMF predictions would constitute and upper bound

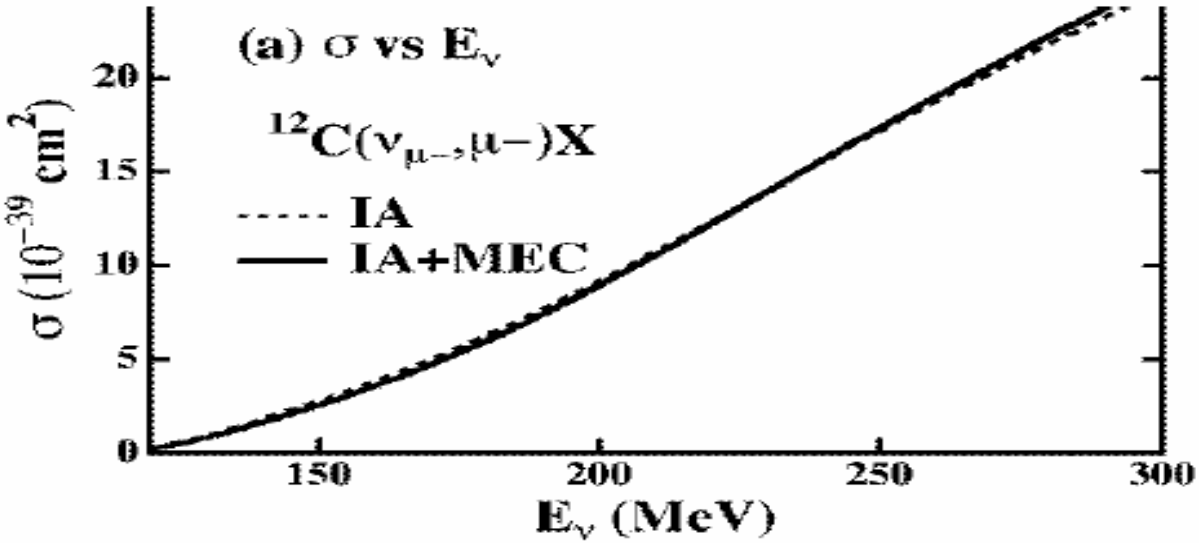
Summary

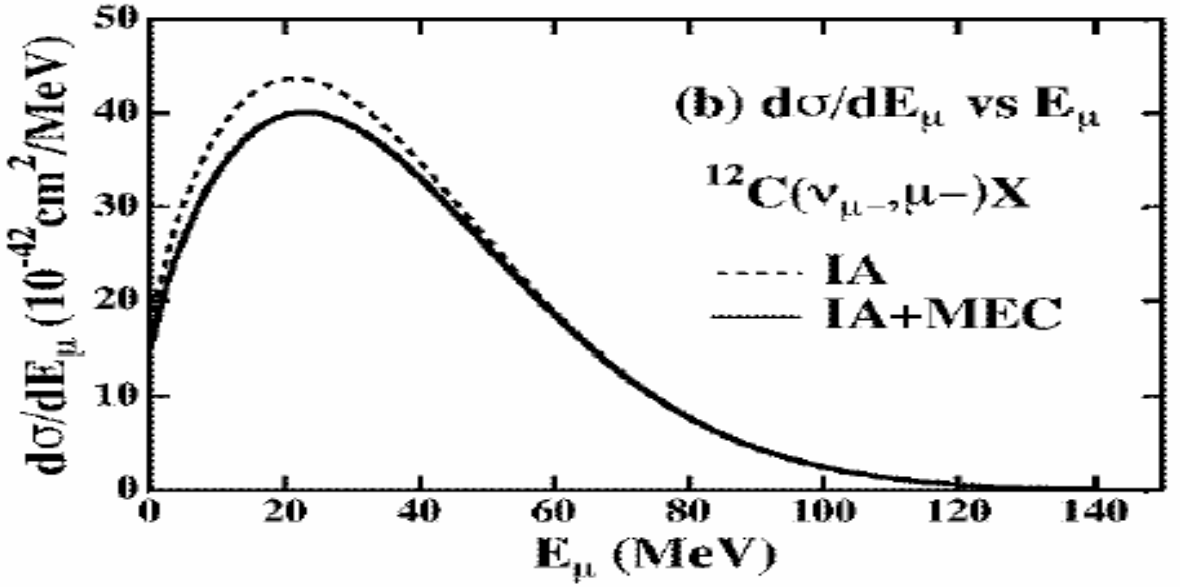
(5) Neutrino reactions from say 100's MeV to several GeV, where the RMF shows good agreement with (e,e') data, can be predicted. FSI effects in the cross-sections are not negligible

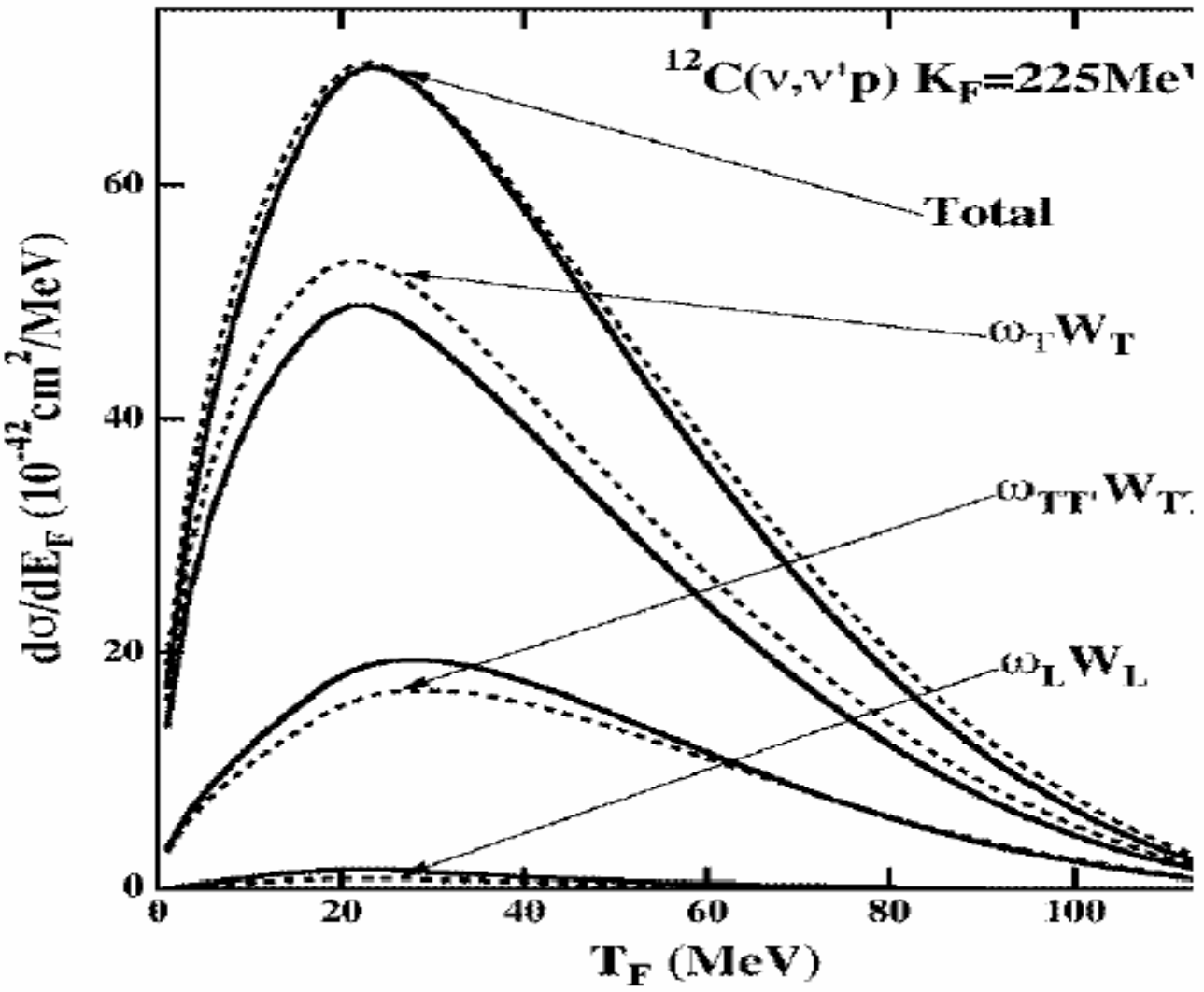
(6) In the comparison of models/theories to experiment, care must be taken to the exclusive/inclusive actual experimental combination

(7) For inclusive observables, for which the kinematics and phase space are smoothed it seems that the impulse approximation and the relativistic mean field, in spite of its simplicity, do a very decent job

(8) Alternatively, the scaling approach allow for model independent description of the nuclear response in neutrino scattering, as an alternative to RFG


(a) σ vs E_ν
$^{12}C(\nu_{\mu^-},\mu^-)X$
IA
IA+MEC
σ (10^{-39} cm^2)
E_ν (MeV)
0
5
10
15
20
150
200
250
300


(b) dσ/dE_μ vs E_μ
$^{12}C(\nu_{\mu^-},\mu^-)X$
IA
IA+MEC
dσ/dE_μ (10^{-42} cm^2/MeV)
E_μ (MeV)
0
10
20
30
40
50
0
20
40
60
80
100
120
140


^{12}C(ν,ν'p) K_F=225Me
Total
$\omega_T W_T$
$\omega_{TT'} W_{T'}$
$\omega_L W_L$
$d\sigma/dE_F$ (10^{-42}cm^2/MeV)
T_F (MeV)
0
20
40
60
80
100

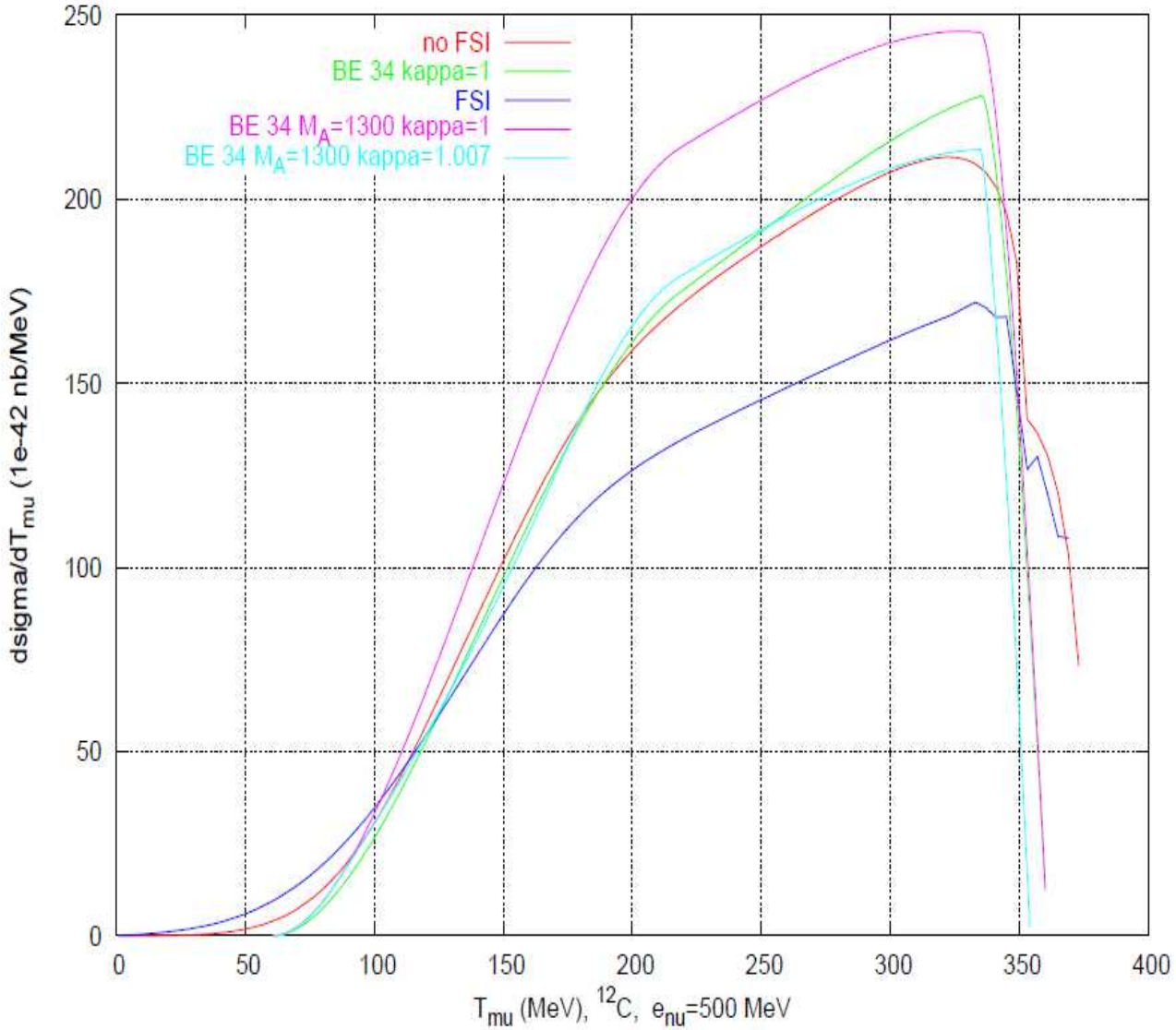
What about the enhancement of the lower components?.

- We can put artificially 'on shell' the initial and final nucleon by forcing their wave functions to fullfill 'half' *free* Dirac equation
- Gordon transformation will be valid for these EMA spinors, and matrix element should factorize into the ones for free nucleons
- Show that the previous current operator are equivalent for EMA (on-shell) spinors

$$\bullet\ \psi_{RDWIA}(\vec{p}) = \begin{pmatrix} \psi_{up}(\vec{p}) \\ \frac{\vec{\sigma}\cdot\vec{p}}{E+M+S-V}\psi_{up}(\vec{p}) \end{pmatrix} \rightarrow$$

$$\psi_{EMA}(\vec{p}) = \begin{pmatrix} \psi_{up}(\vec{p}) \\ \frac{\vec{\sigma}\cdot\vec{p}_{as}}{E_{as}+M}\psi_{up}(\vec{p}) \end{pmatrix}$$

Effect of RFG parameters



Increasing the axial mass changes the cross-section significantly

kappa parameter returns it to a place near ordinary RFG

There is still the effect of FSI

Other handles to tune: H_p