The Electroweak Nuclear Response in the Impulse Approximation Regime

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References

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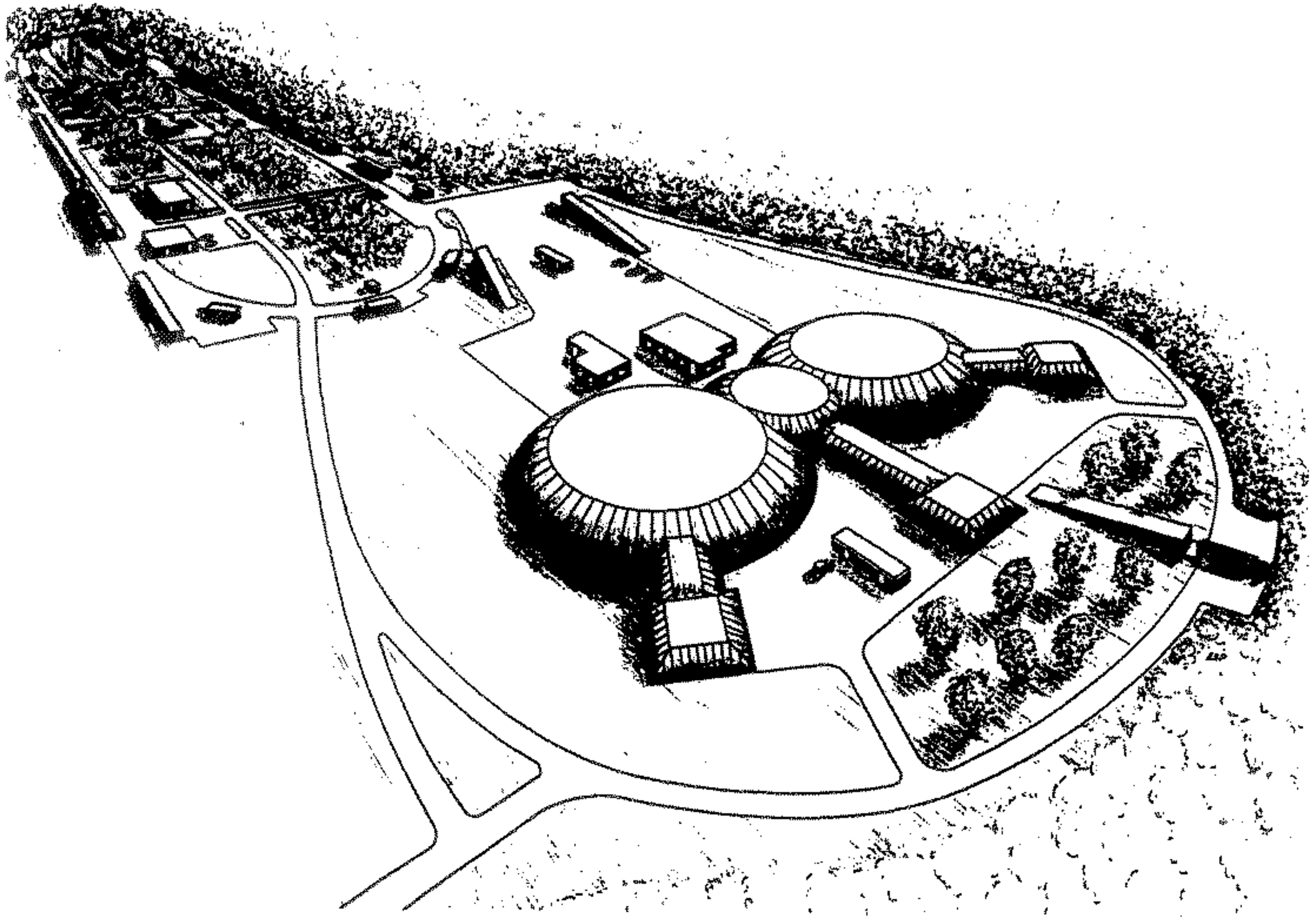
PROCEEDINGS FROM THE WORKSHOP ON SHORT-RANGE STRUCTURE IN NUCLEI

HELD AT CEBAF

MARCH 15 - 16, 1996



FOREWORD

The short-distance structure of the nucleus is certainly one of the frontiers of nuclear physics.

While QCD will some day provide a *rationale* for our standard nuclear physics model of nucleons interacting *via* an effective potential, it will not affect our understanding of long-distance nuclear physics in terms of this very successful approximation. In contrast, at short distances there is every reason to expect the nucleon picture of the nucleus to break down in favor of the quark-gluon degrees of freedom. Ideally, an "inside-out" description which starts at short distance can help us to understand not only where standard nuclear physics breaks down, but also why it works so well in its domain of applicability.

In March 1996, under the organization of Robert Lourie, Eddy Offerman, Vijay Pandharipande, and Rocco Schiavilla, we held a workshop on "Short-Range Structure in Nuclei" at CEBAF to assess the status of this field and the laboratory's potential contribution to it. This volume is a collection of the transparencies shown by the Workshop speakers. They follow the Workshop program, which is reproduced here. I hope that this primitive archive of this very successful Workshop will be useful to both the participants as a reminder of what they learned, and to others who would like to see what was said.

Nathan Isgur
CEBAF
April 1996

Introductory Remarks

The repulsive core and tensor components of the nucleon-nucleon interaction strongly influence the structure of nuclei at small internucleon separations. Within this central theme, the workshop aimed at two goals. The first was to critically examine the experimental evidence accumulated so far for the presence of correlations induced by these components of the nucleon-nucleon interaction in both inclusive and exclusive electron scattering reactions as well as in photon and pion absorption processes in nuclei and, more importantly, to identify promising new avenues for the investigation of correlation effects that the availability of polarized electron beams, polarized targets and recoil polarimetry will make possible in the near future. Complementary to these aspects was the assessment of the current status of the theoretical description of nuclear ground- and scattering-state wave functions, and of our understanding of the reaction mechanism, in particular the treatment of final state interaction and two-body current contributions. The second goal of the workshop was to review our present understanding of the nucleon-nucleon interaction and of the properties of the two-nucleon system in terms of effective field theories based on chiral perturbation theory, or in terms of basic quark degrees of freedom.

We felt that the workshop was successful on both counts. The response to our initiative from the nuclear physics community was extremely positive, and we are indebted to all speakers and participants for contributing to make the meeting as lively and as fruitful as it was.

It is our pleasure to thank CEBAF, in particular Larry Cardman, John Domingo and Nathan Isgur, for sponsoring the workshop, and the secretarial staff: Mrs. Celsa Echeandia, Carol Mendiola and Timeka Peters, for handling all the logistic and administrative problems with skill and enthusiasm.

Robert Lourie
Eddy Offermann
Vijay Pandharipande
Rocco Schiavilla

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Motivation

- Quantitative understanding of the weak nuclear response at $E_\nu \sim 0.5 - 3$ GeV required for the analyses of high precision neutrino oscillation

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- Need to develop a theoretical framework
  - ▷ applicable to a wide range of kinematical conditions and targets
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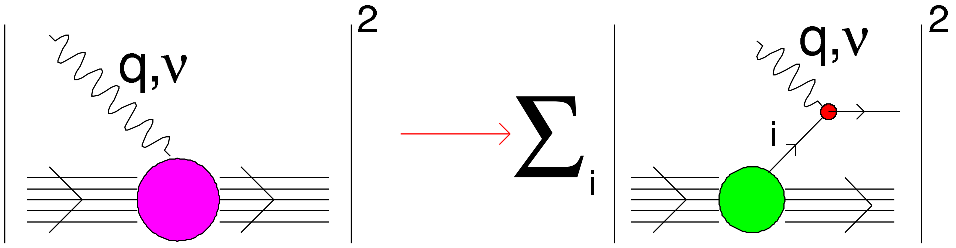
- Quantitative understanding of the weak nuclear response at $E_\nu \sim 0.5 - 3$ GeV required for the analyses of high precision neutrino oscillation
- Need to develop a theoretical framework
  - ▷ applicable to a wide range of kinematical conditions and targets
  - ▷ easily implementable in Monte Carlo simulations
- Much information can be extracted from the results of experimental and theoretical studies of electron-nucleus scattering

The $\ell + A \to \ell' + X$ x-section in the IA regime

In the Impulse Approximation scheme (IA) the scattering process off a nucleus reduces to the incoherent sum of elementary processes involving individual nucleons:



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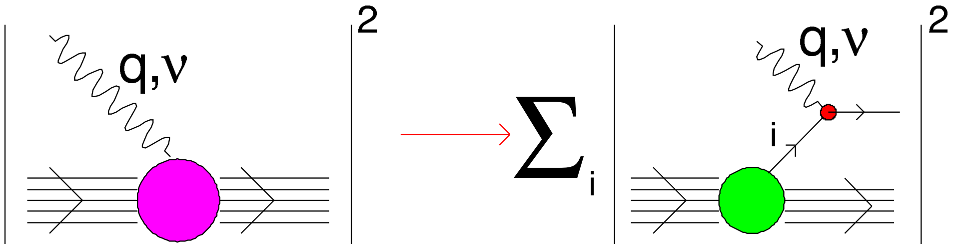

The x-section reduces to

$$\frac{d\sigma_A}{d\Omega_{\ell'} dE_{\ell'}} = \int d^4p \, P(p) \left(\frac{d\sigma_N}{d\Omega_{\ell'} dE_{\ell'}} \right)$$

- Target spectral function

$$P(\mathbf{p}, E) = \sum_n |\langle \Psi_n^{(A-1)} | a_{\mathbf{p}} | \Psi_0^A \rangle|^2 \delta(E + E_0 - E_n)$$

probability of removing a nucleon of momentum $\mathbf{p}$ from the target, leaving the residual spectator system with excitation energy E

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- Elementary cross-section ($e+N\to\ e'+X$ as an example)

$$\frac{d\sigma_{eN}}{d\Omega_{e'}dE_{e'}}=\frac{\alpha^2}{Q^4}\frac{E_e'}{E_e}\ \frac{m}{E_{\mathbf{p}}}L_{\mu\nu}W_N^{\mu\nu}$$

$$W_N^{\mu\nu}=W_1^N\left(-g^{\mu\nu}+\frac{q^\mu q^\nu}{q^2}\right)+\frac{W_2^N}{m^2}\left(p^\mu-\frac{(pq)}{q^2}q^\mu\right)\left(p^\nu-\frac{(pq)}{q^2}q^\nu\right)$$

Nuclear Many-Body Theory (NMBT)

- Bottom line: want to decouple the uncertainty associated with dynamical models from the approximations implied in many many-body calculations

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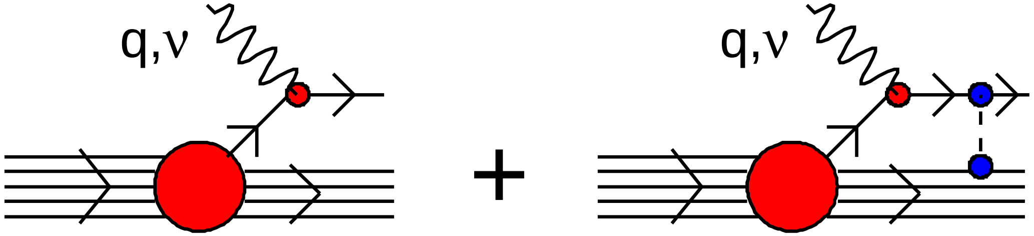
- The nucleon structure functions can be directly measured (or extracted from measurements)
- Calculation of nuclear observables *does not involve any adjustable parameters*

Corrections to IA

- Final State Interactions (FSI): needed to explain exclusive data



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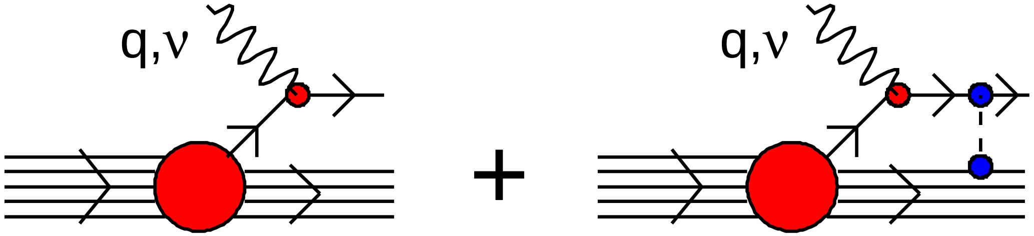

- ▷ mean field of the spectators → energy shift
- ▷ coupling of $1p1h$ final state to $np-nh$ → redistributions of the strenght

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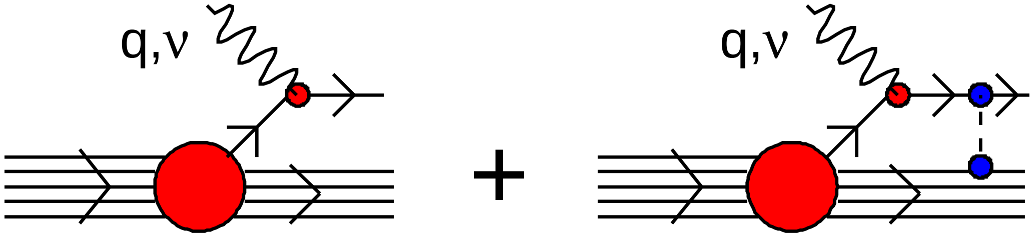

▷ mean field of the spectators → energy shift

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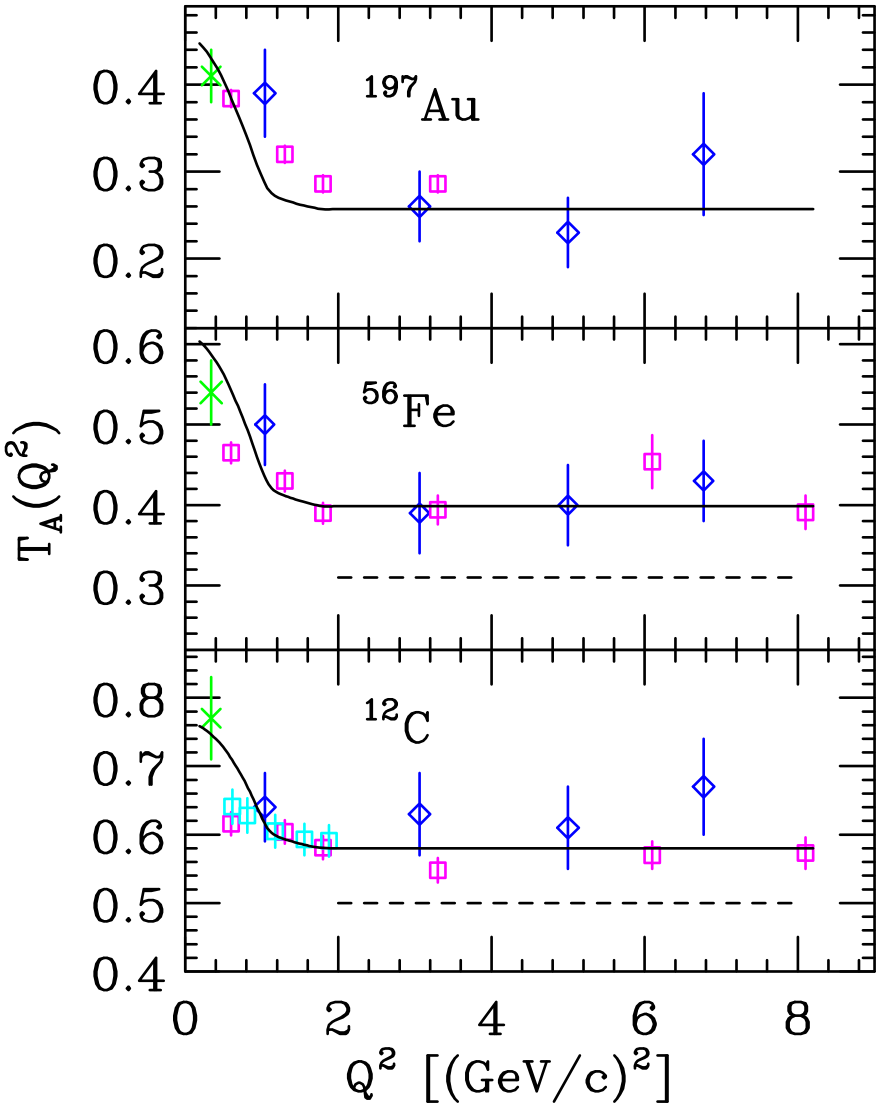
- High energy approximation (eikonal trajectory + *frozen* spectators): calculations carried out using (many-particle) density distributions from NMBT and measured scattering amplitude (again, *no adjustable parameters !*).

Nuclear transparency (recall: no FSI $\rightarrow T_A \equiv 1$)



- ▷ Calculated nuclear transparency compared to MIT-Bates, SLAC and JLab data
- ▷ Good overall agreement between theory and experiment
- ▷ Complicated pattern of correlation effects, leading to a sizable enhancement of the transparency

Corrections to IA (continued)

Effects of Pauli blocking → *statistical* FSI

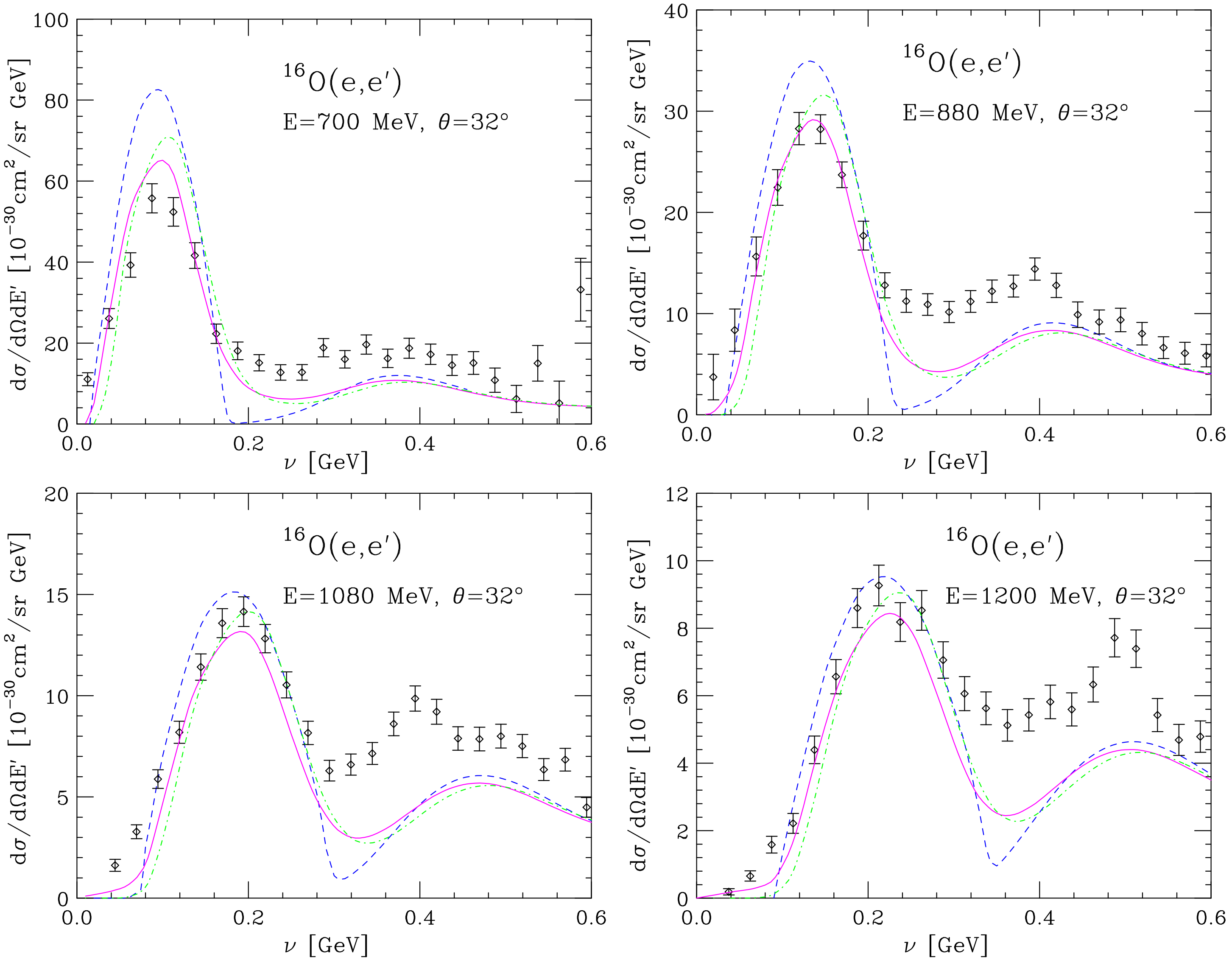
A rather crude prescription: modify the spectral function according to

$$P(\mathbf{p},E) \to \; P(\mathbf{p},E)\,\theta(|\mathbf{p}+\mathbf{q}| - \overline{p}_F)$$

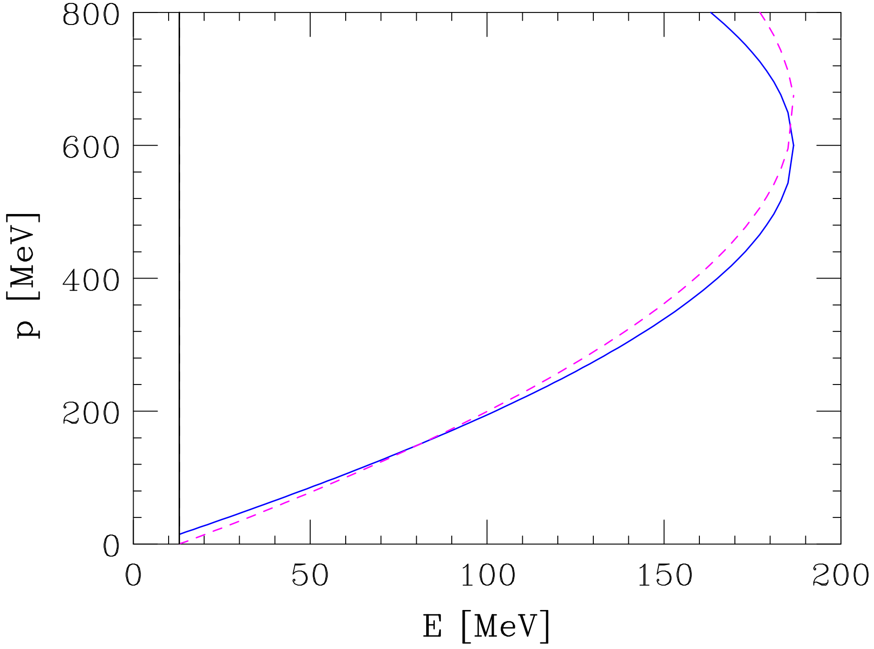
$$\overline{p}_F = \int d^3r\;\rho_A(\mathbf{r})p_F(\mathbf{r}) \quad , \quad p_F(\mathbf{r}) = \left[\frac{3}{2}\pi^2\rho_A(\mathbf{r})\right]^{1/3}$$

For beam energies in the few GeV region the effect of Pauli blocking is hardly visible in the energy spectrum of the outgoing lepton at fixed angle. However, it becomes dominant in the Q^2 distribution for $Q^2 < 0.2$ GeV^2.

Comparison to LNF ^{16}O (e, e') data **(Anghinolfi *et al*, 1996)**

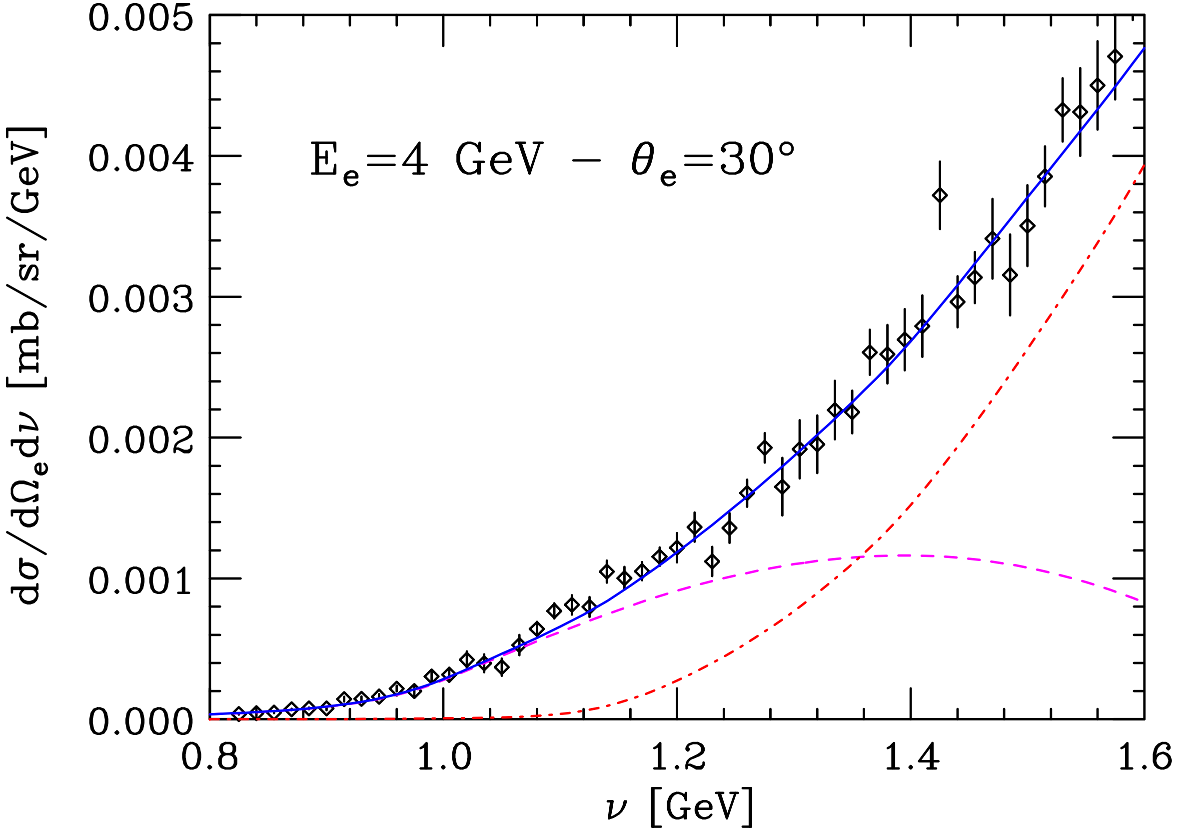


- Theoretical results $\sim$ OK in the region of quasi elastic peak
- data significantly underestimated above π production threshold
- deficiencies of the SF unlikely, as calculation of quasi elastic and Δ-production x-sections involve integration regions almost exactly overlapping one another



- Comparison to data at larger Q^2

▷ $A \to \infty$ extrapolation of SLAC data @ $Q^2 \sim 2$ GeV^2

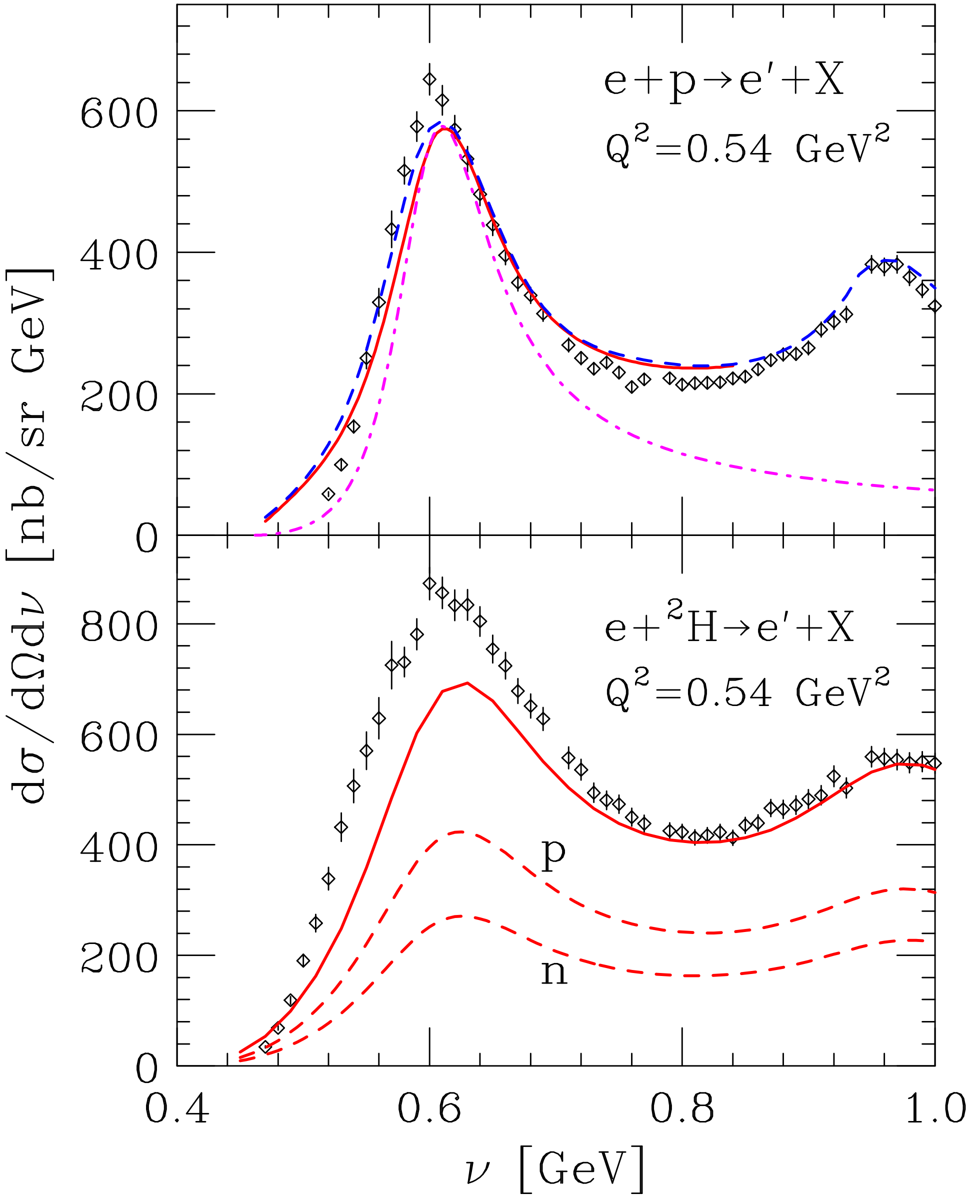


- problems likely to be ascribable to the description of W_1^N and W_2^N in the Δ production region at low Q^2

How well do we know Δ production at low Q^2 ?

- Oxygen results obtained using Bodek-Ritchie (BR) model of the nucleon structure functions, resulting from a global fit to SLAC data
- Main features of the BR model
  - ▷ provides $W^N_{1,2}$ for both proton and neutron
  - ▷ neutron structure function are obtained combining proton and deuteron data and unfolding nuclear effetcs
  - ▷ extends over a broad kinematical region, including both resonance production and deep inelastic scattering
  - ▷ only includes data with $Q^2 \gtrsim 1 \text{ GeV}^2$. Use at lower Q^2 involves an extrapolation

JLab $e-p$ **and** $e-d$ **data at low** Q^2



- Fits and dynamical models provide a good account of proton data
- The BR model fails to reproduce the deuteron data at $Q^2 \sim .5$ GeV^2
- Problems with the neutron structure functions !

- Systematic uncertainty in the BR treatment of nuclear effect (deuteron wf, relativistic normalization of $n(\mathbf{p})$, FSI) small
- Estimate $W_{1,2}^{n}$ *à la* BR from JLab data @ $Q^2 \sim 5$ GeV^2
  - ▷ write the deuteron cross section as

$$\sigma_d = \widetilde{\sigma}_p + \widetilde{\sigma}_n$$

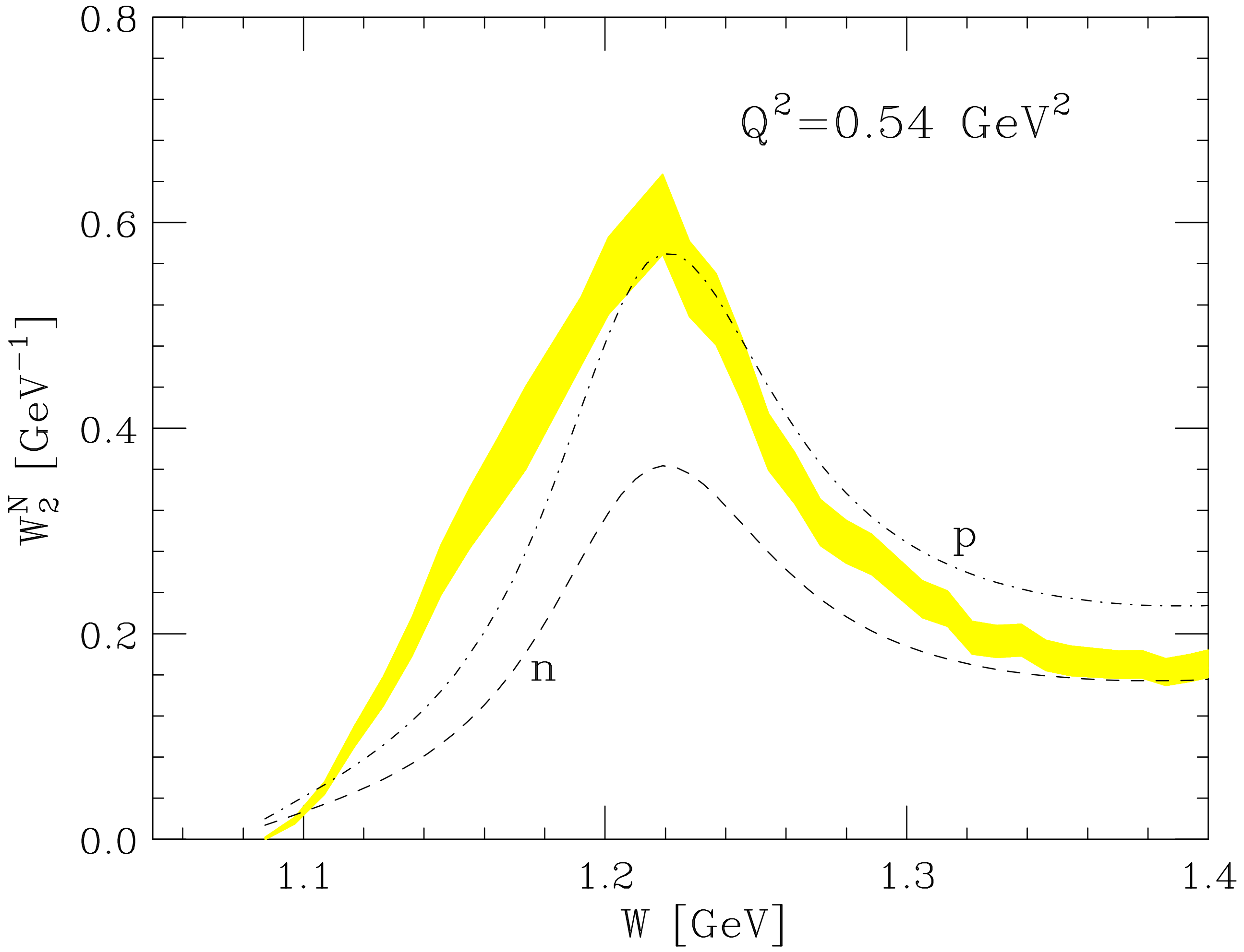
    where $\widetilde{\sigma}_{p,n}$ are the smeared p and n x-sections.
  - ▷ define the smearing ratio

$$S_p = \frac{\sigma_p}{\widetilde{\sigma}_p}$$

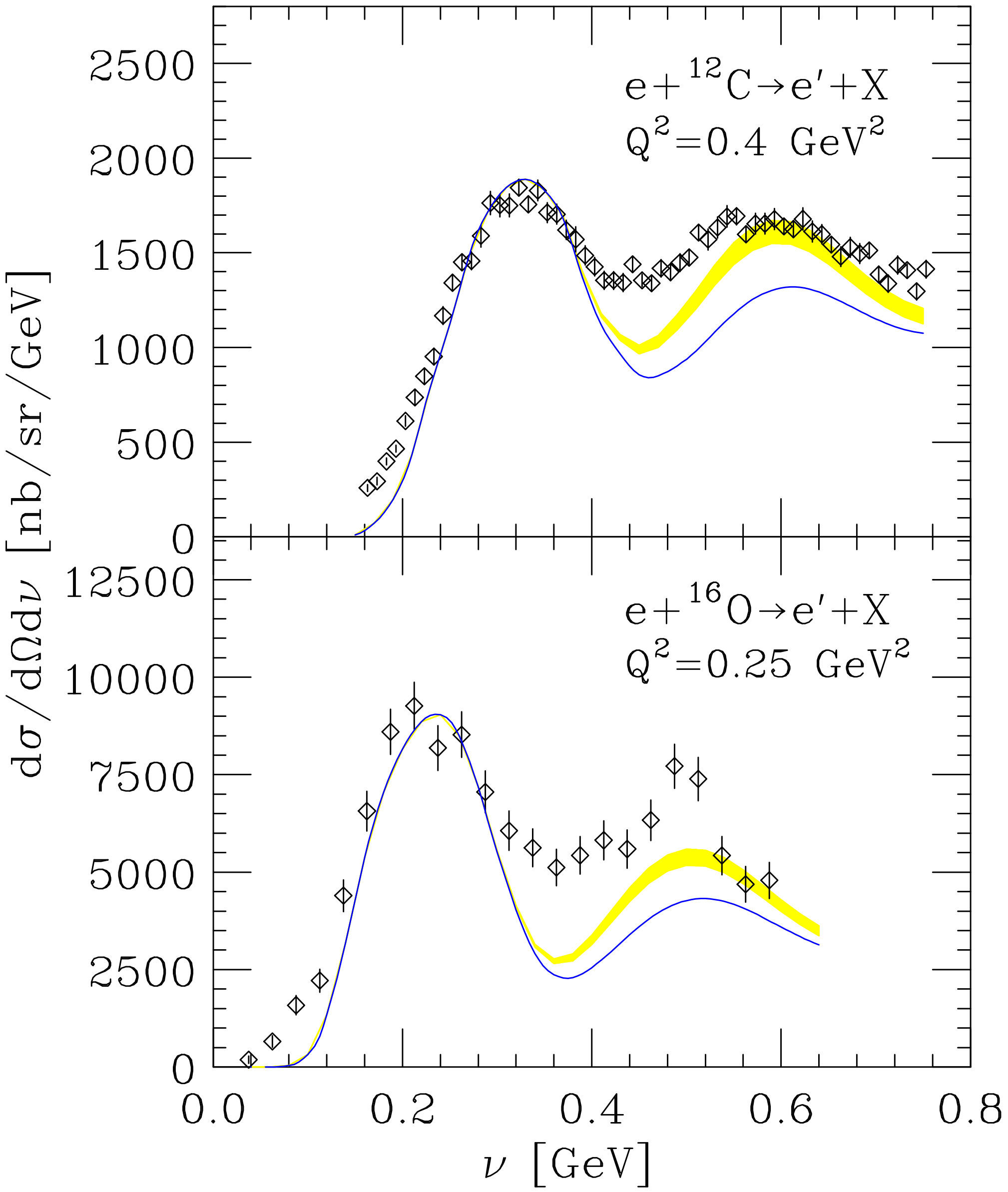
  - ▷ Assuming $S_p \approx S_n$

$$\sigma_n = S_n \widetilde{\sigma}_n \approx S_p \sigma_d - \sigma_p$$

W_2^n from data @ $E_e = 2.445$ GeV and $\theta_e = 20°$



Nuclear cross sections



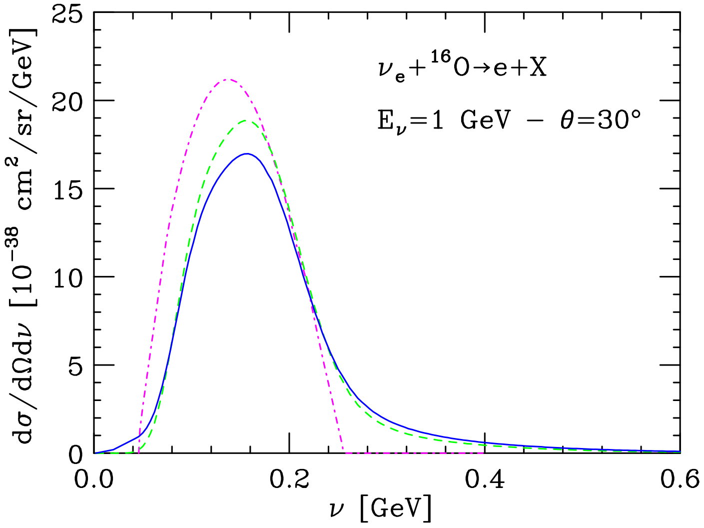
- SLAC data

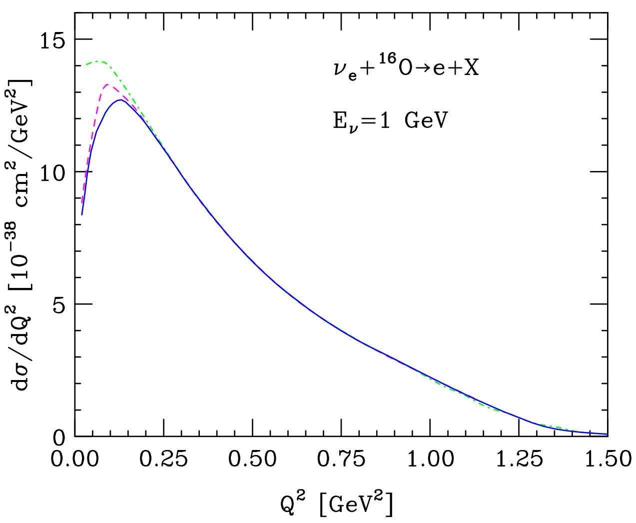
  (Sealock *et al* (1989))

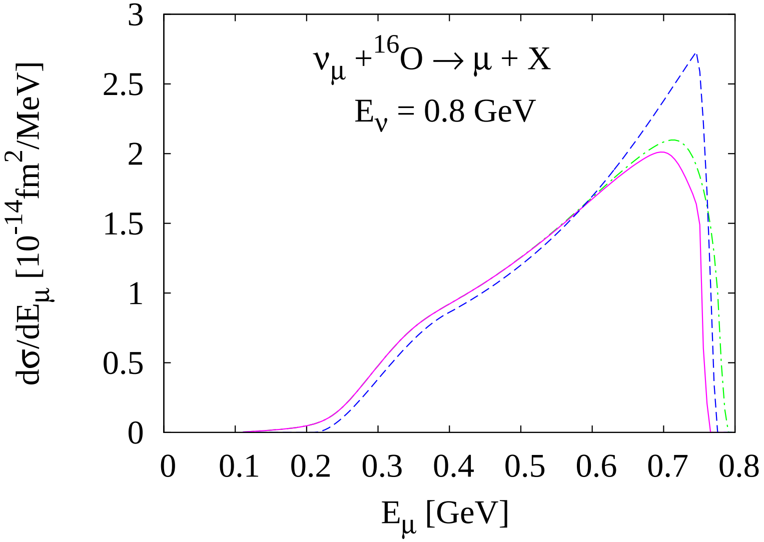
- LNF data

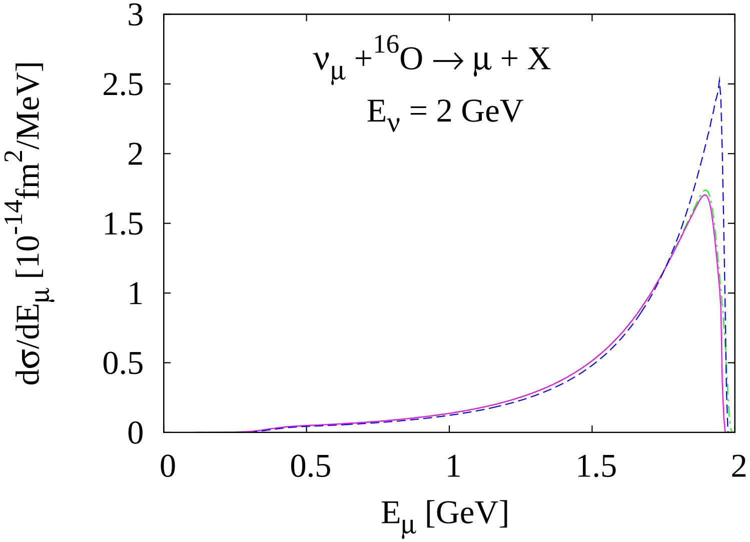
  (Anghinolfi *et* al (1996))

Results for ^{16}O (ν_e, e) scattering

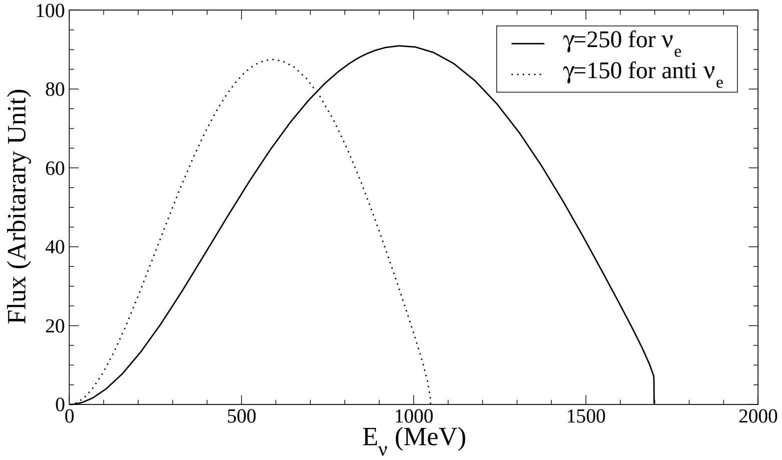


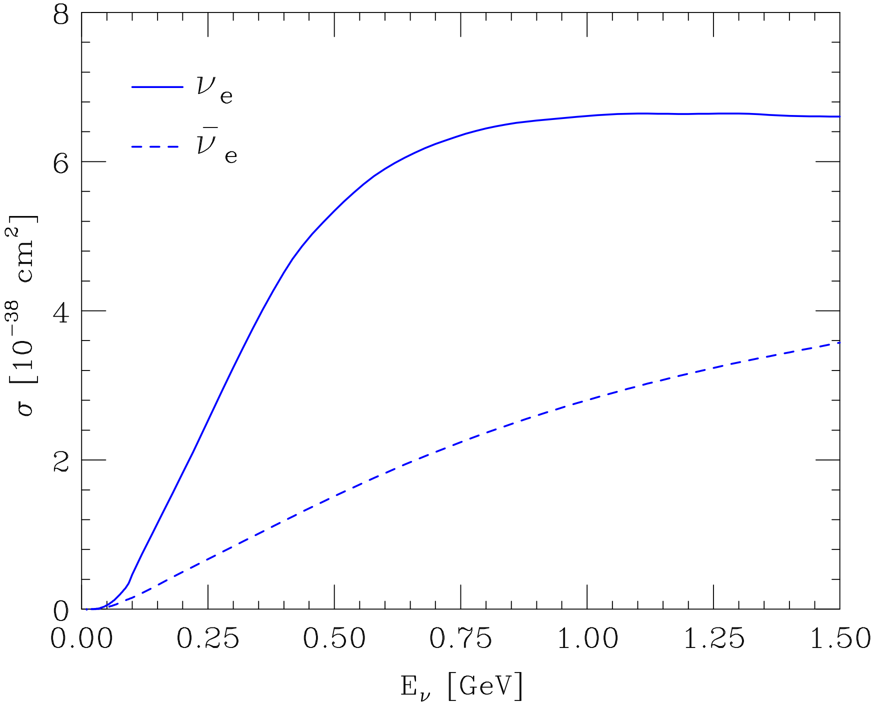




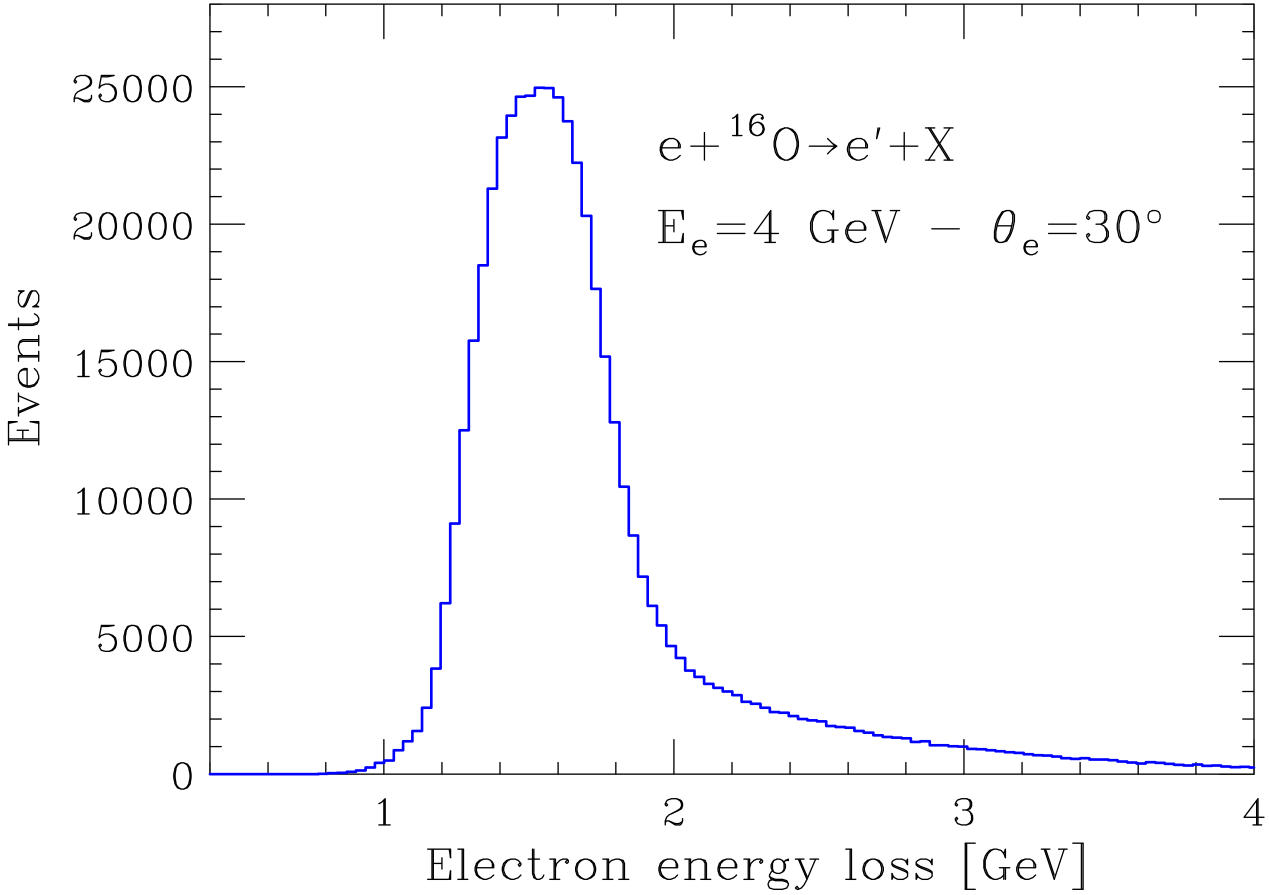


Total cross section for β-beams of ν_e and $\bar{\nu}_e$ (QE only)





Monte Carlo simulation of $e +^{16} O \rightarrow e' + X$



Conclusions and prospects

- Quantitative parameter free calculations of the electroweak nuclear response for beam energies up to few GeV appear to be feasible
  - ▷ QE scattering under control
  - ▷ A better understanding of the Δ production region requires more data at low Q^2, needed to further constrain fits and models of the nucleon structure functions
  - ▷ The role of meson exchange currents in the dip region needs to be carefully investigated