Inclusive Inelastic Electron-Nucleus Scattering at Large Momentum Transfers and x > 1

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International Workshop on
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Het Pand, Ghent University, Ghent, Belgium

Outline

- Introduction to, the basic features of and existing kinematic coverage
- Correlations in inclusive scattering
- y-scaling and its limitations
- SRC and ratios
- x - and ξ-scaling
- Prospects at 11 GeV

Introduction

Inclusive electron scattering from nuclei provides a rich, yet complicated mixture of physics that has yet to be fully exploited.

- Momentum distributions and the spectral function S(k,E).
- Short Range Correlations and Multi-Nucleon Correlations
- Scaling (x, y, φ', ξ)
- Medium Modifications -- tests of EMC; 6-quark admixtures
- Duality
- Superfast quarks => partons that have obtained momenta $x > 1$

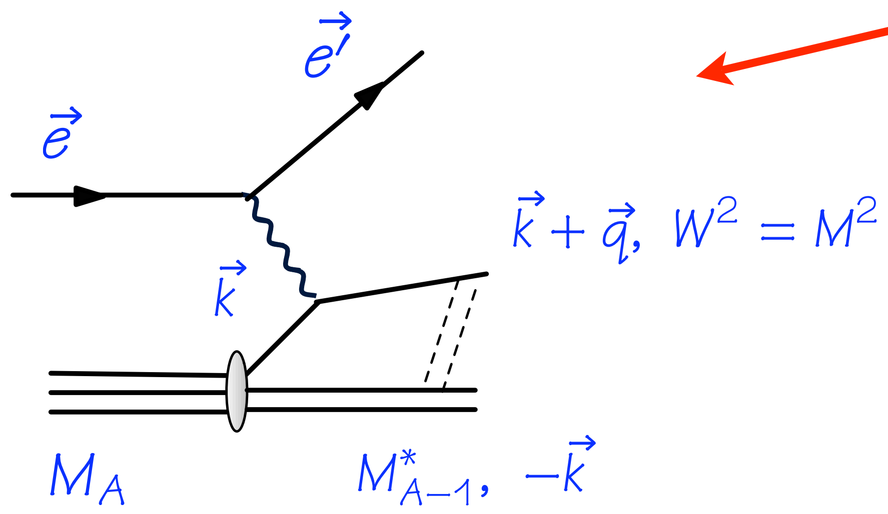
The inclusive nature of these studies make disentangling all the different pieces a challenge but experiments over a range of Q^2 and with different A will help.

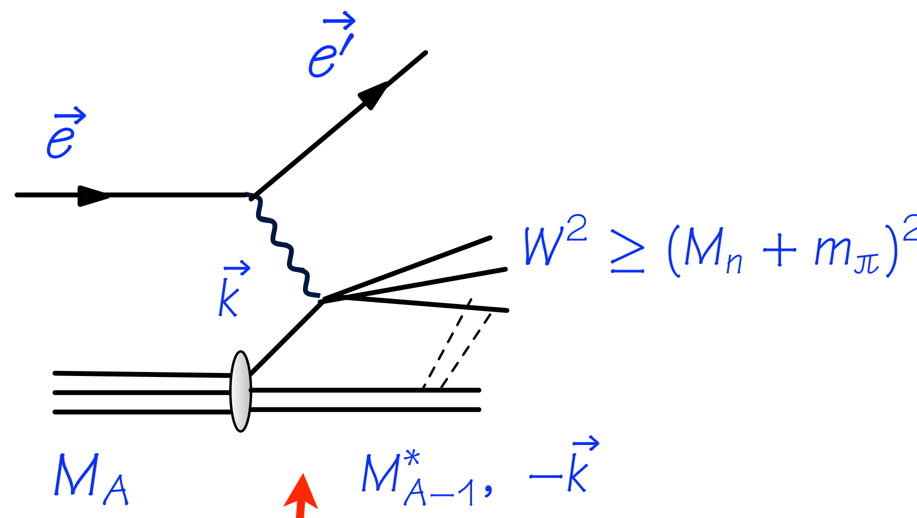
Interpretation demands theoretical input

Inclusive Electron Scattering from Nuclei

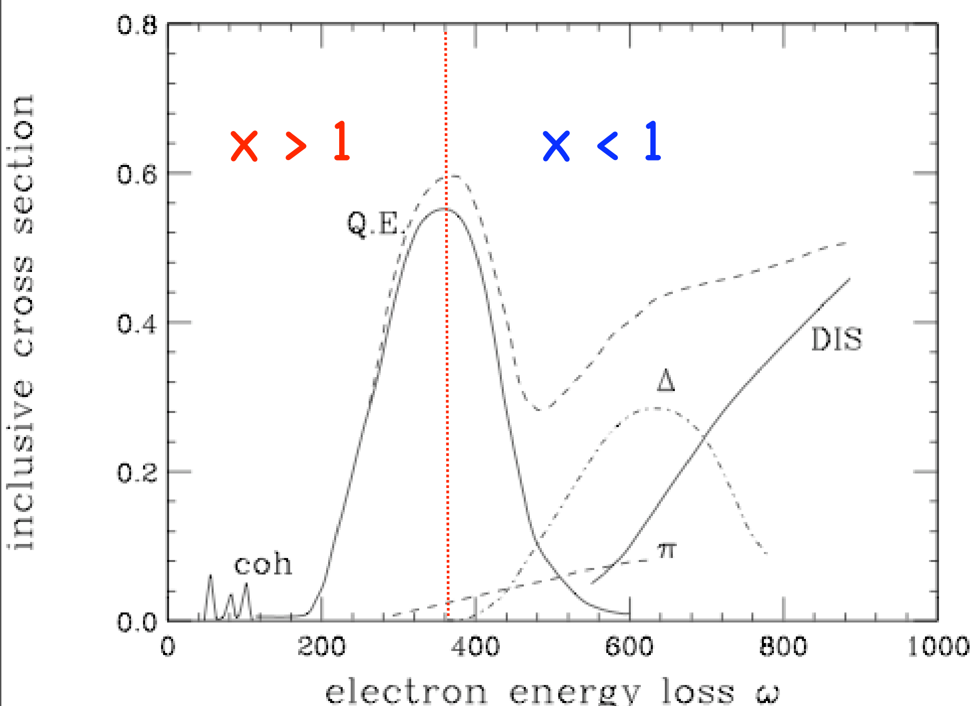
Two distinct processes

Quasielastic from the nucleons in the nucleus





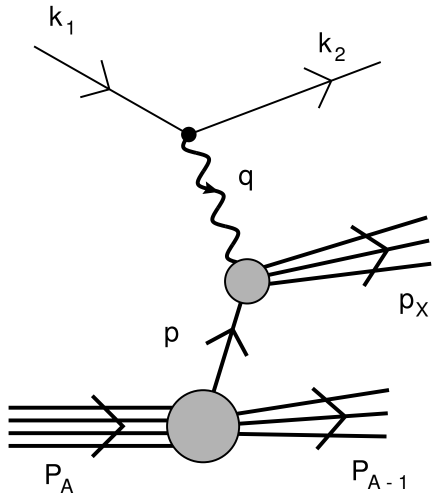
Inelastic and DIS from the quark constituents of the nucleon.



Inclusive final state means no separation of two dominant processes

$x = Q^2/(2m\upsilon)$

υ,ω=energy loss



$$\frac{d\sigma^2}{d\Omega_{e'} dE_{e'}} = \frac{\alpha^2}{Q^4}\frac{E'_e}{E_e} L_{\mu\nu}W^{\mu\nu}$$

There is a rich, if complicated, blend of nuclear and fundamental QCD interactions available for study from these types of experiments.

The two processes share the same initial state

QES in IA $$\frac{d^2\sigma}{d\Omega d\nu} \propto \int d\vec{k} \int dE \sigma_{ei} \underbrace{S_i(k,E)}_{\text{Spectral function}} \delta()$$

The limits on the integrals are determined by the kinematics. Specific (x, Q^2) select specific pieces of the spectral function.

DIS $$\frac{d^2\sigma}{d\Omega d\nu} \propto \int d\vec{k} \int dE \, W_{1,2}^{(p,n)} \underbrace{S_i(k,E)}_{\text{Spectral function}}$$

$$n(k) = \int dE \; S(k,E)$$

However they have very different Q^2 dependencies

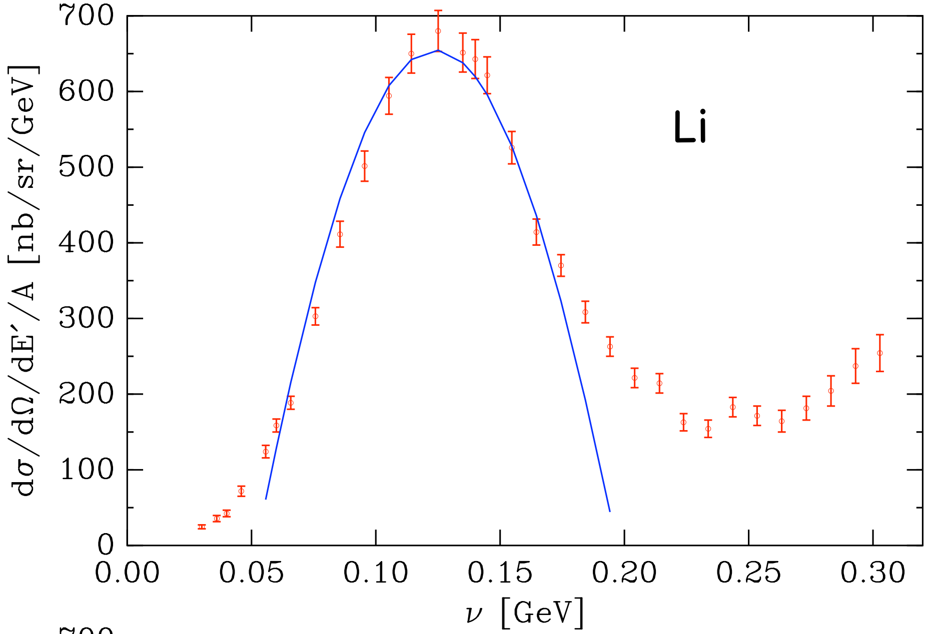
$\sigma_{ei} \propto$ elastic (form factor)^2 $\quad$ $W_{1,2}$ scale with ln Q^2 dependence

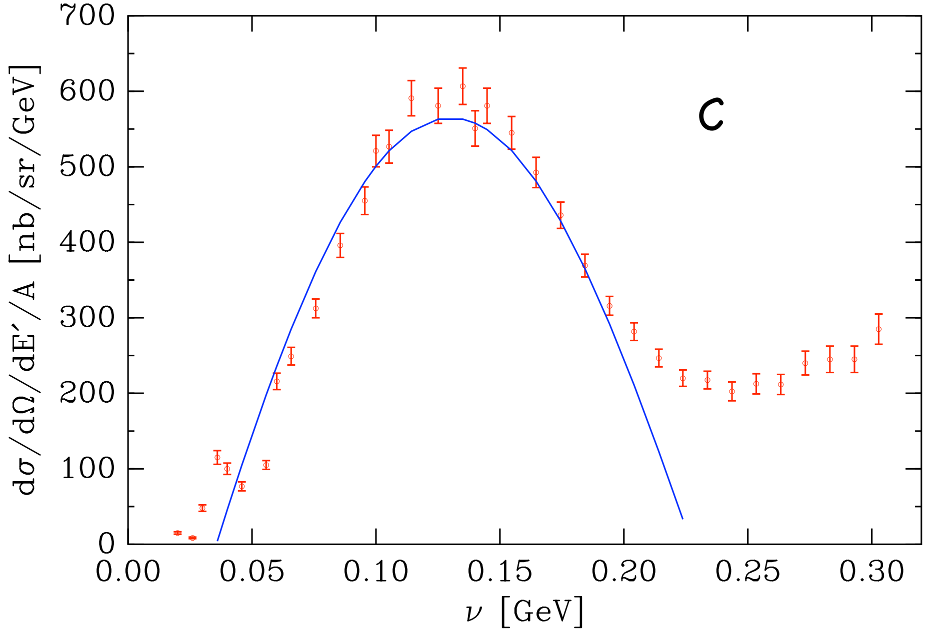
Exploit this dissimilar Q^2 dependence

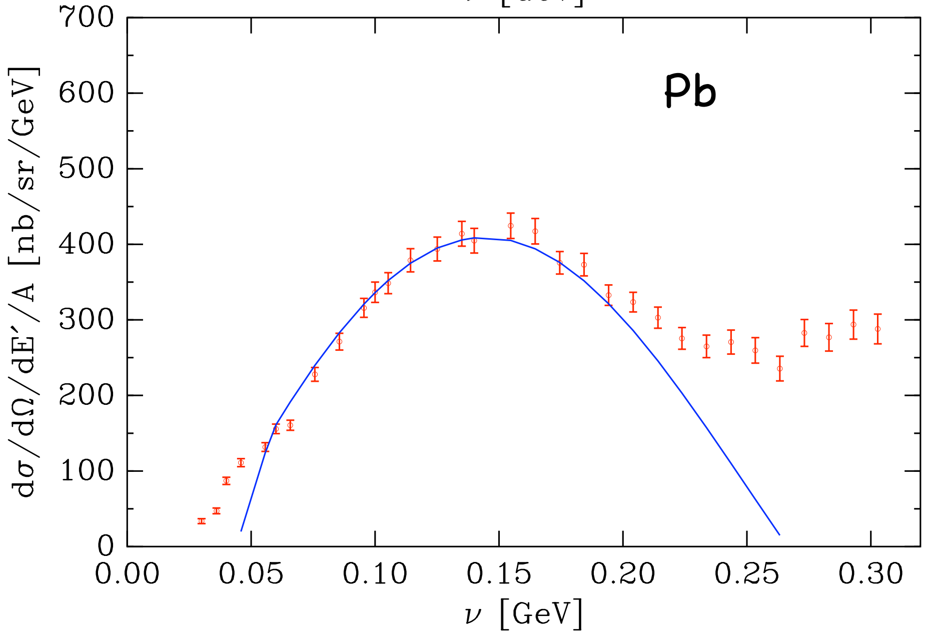
Early 1970's Quasielastic Data

500 MeV, 60 degrees

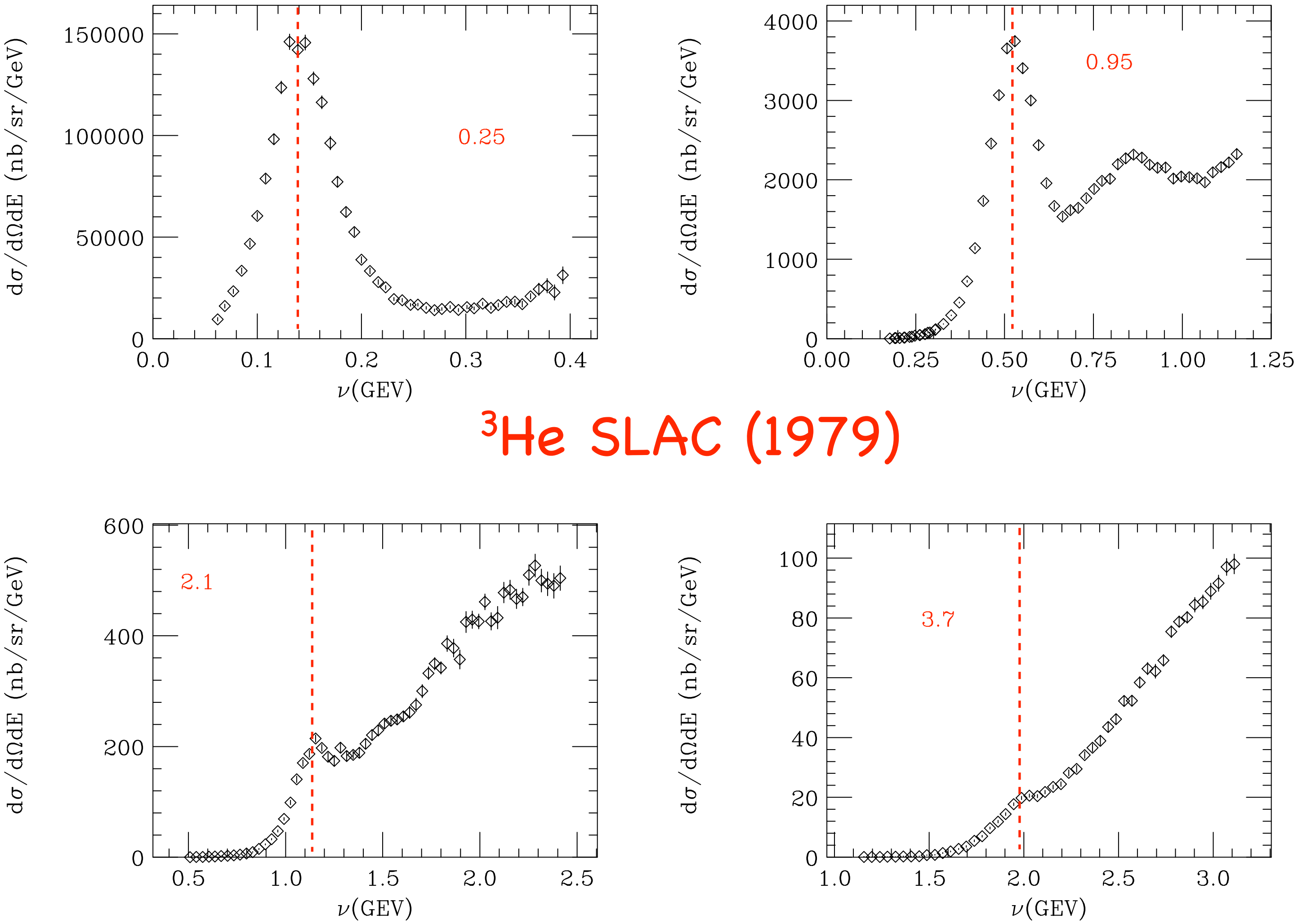
$\vec{q} \simeq 500 MeV/c$







Nucleus	k_F	$\bar{\epsilon}$
^{6}Li	169	17
^{12}C	221	25
^{24}Mg	235	32
^{40}Ca	251	28
^{nat}Ni	260	36
^{89}Y	254	39
^{nat}Sn	260	42
^{181}Ta	265	42
^{208}Pb	265	44



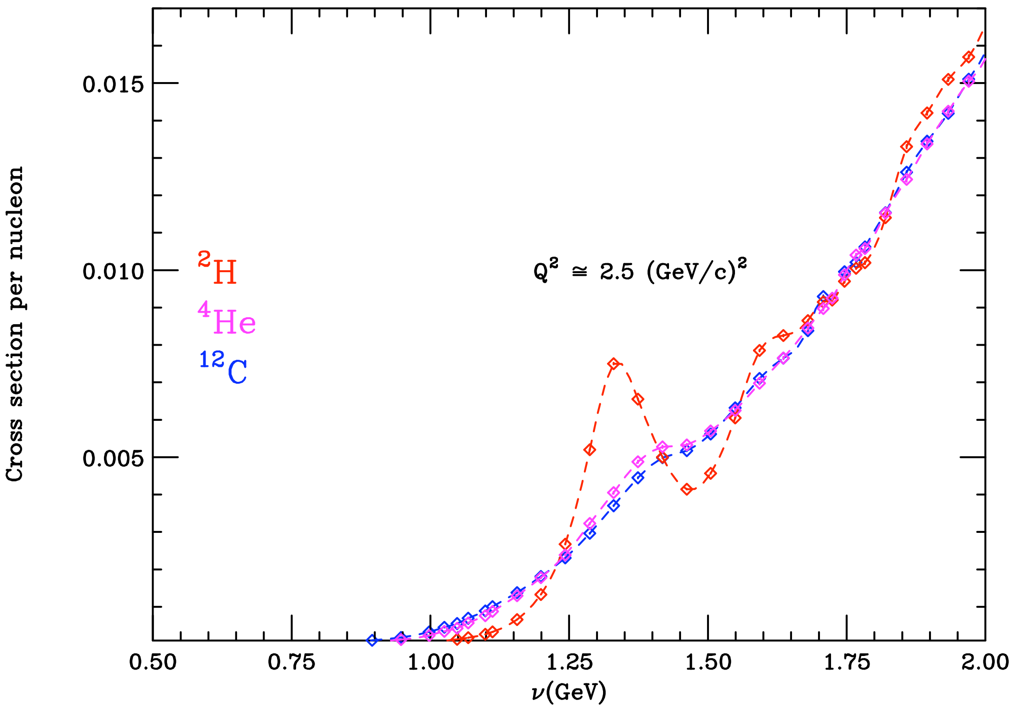
^{3}He SLAC (1979)

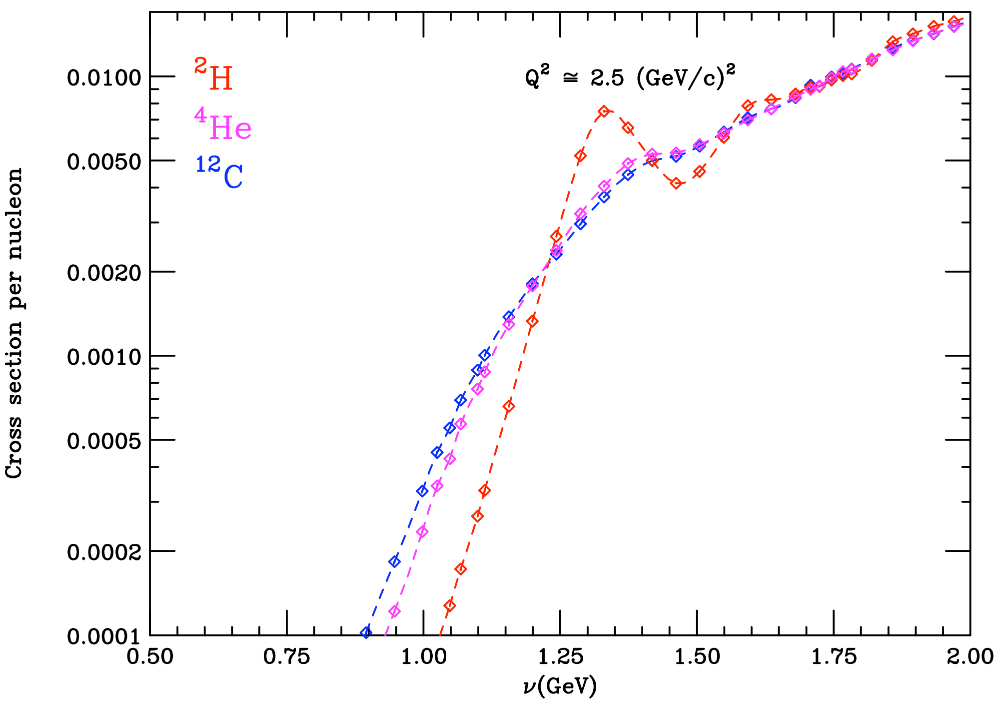
The quasielastic peak (QE) is broadened by the Fermi-motion of the struck nucleon.

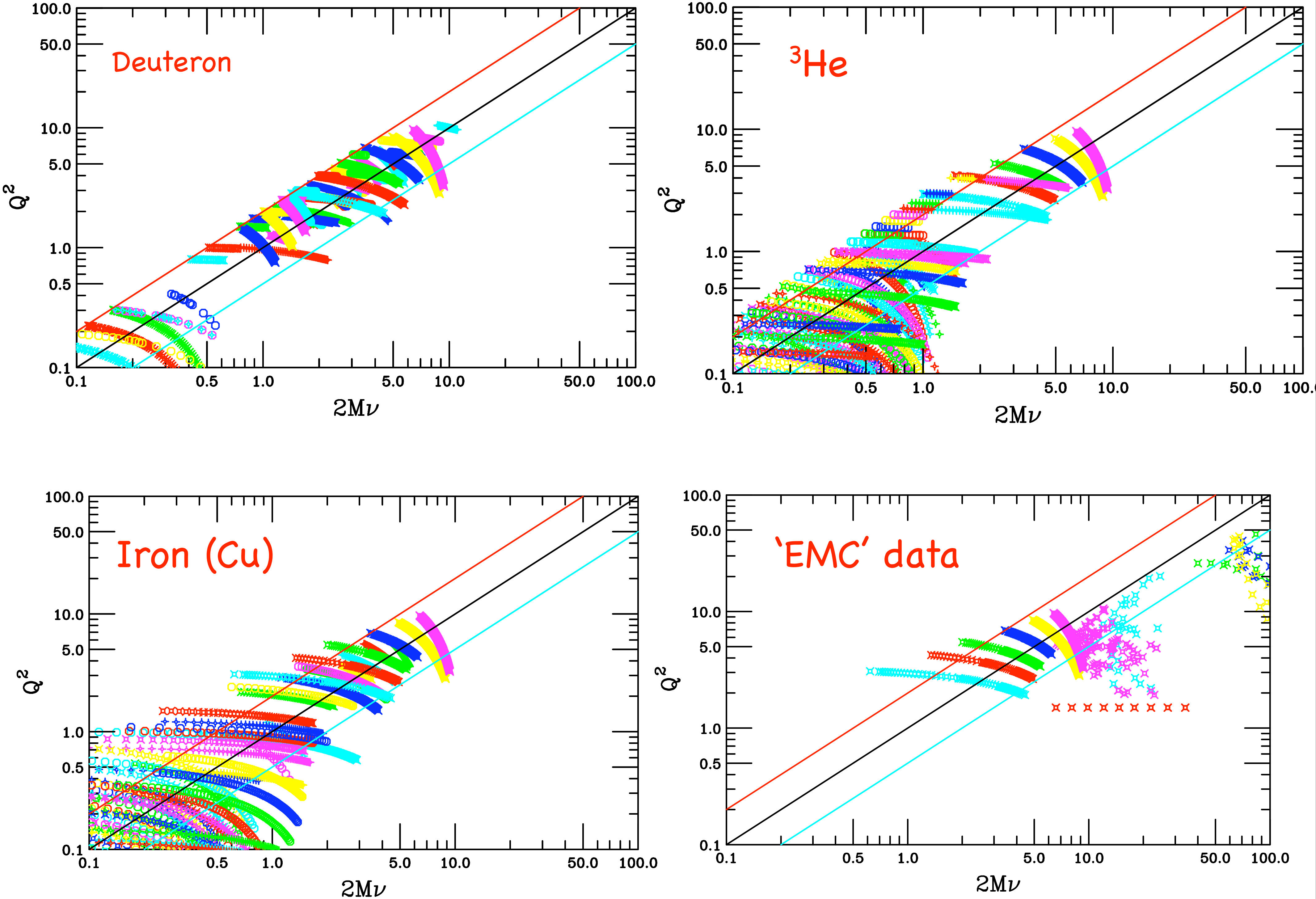
The quasielastic contribution dominates the cross section at low energy loss (ν) even at moderate to high Q^2.

- The shape of the low ν cross section is determined by the momentum distribution of the nucleons.
- As Q^2 >> inelastic scattering from the nucleons begins to dominate
- We can use x and Q^2 as knobs to dial the relative contribution of QES and DIS.

A dependence: higher internal momenta broadens the peak






Deuteron
^{3}He
Iron (Cu)
'EMC' data
Q^2
$2M\nu$

http://faculty.virginia.edu/qes-archive/index.html

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- Acknowledgements

Quasielastic Electron Nucleus Scattering Archive

Welcome to Quasielastic Electron Nucleus Scattering Archive

In connection with a review article (Quasielastic Electron-Nucleus Scattering, by O. Benhar, D. Day and I. Sick) to be submitted to Reviews of Modern Physics, we have collected here an extensive set of quasielastic electron scattering data in order to preserve and make available these data to the nuclear physics community.

We have chosen to provide the cross section only and not the separated response functions. Unless explicitly indicated the data do not include Coulomb corrections.

Our criteria for inclusion into the data base is the following:

1. Data published in tabular form in journal, thesis or preprint.
2. Radiative corrections applied to data.
3. No known or acknowledged pathologies

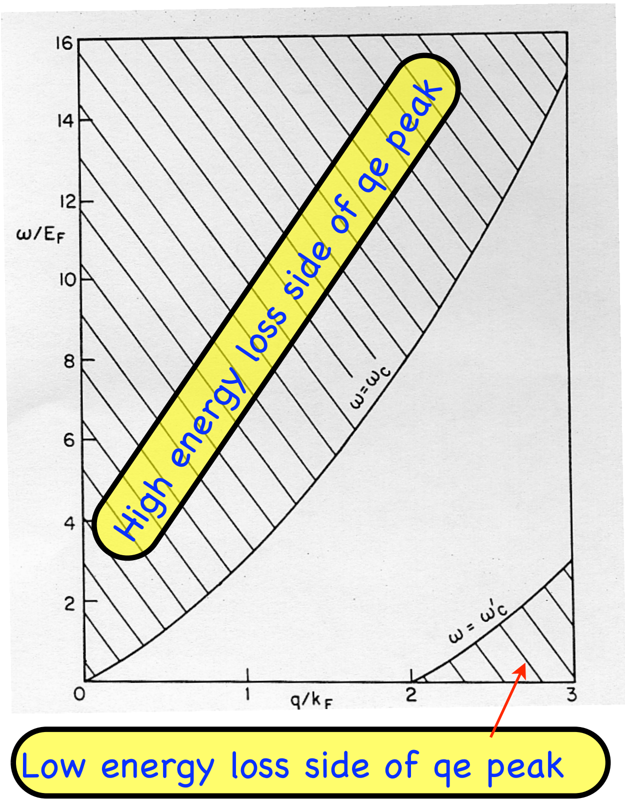
At present there are about 600 different combinations of targets, energies and angles consisting of some 19,000 data points.

In the infrequent event that corrections were made to the data after the original publications, we included the latest data set, adding an additional reference, usually a private communication.

As additional data become known to us, we will add to the data sets.

If you wish to be alerted to changes in the archive or to the inclusion of new data, send an email to me. Send any comments or corrections you might have as well.

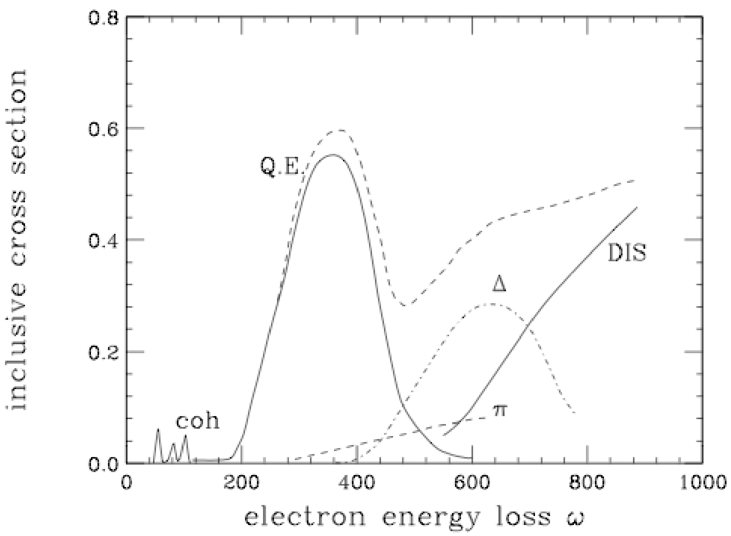
Correlations and Inclusive Electron Scattering

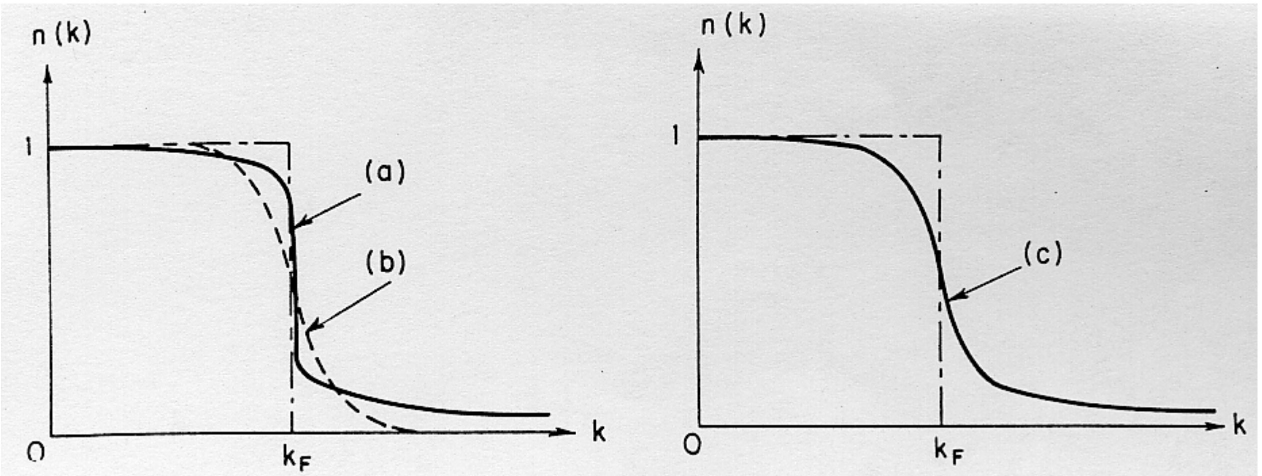


Shaded domain where scattering is restricted solely to correlations. Czyz and Gottfried (1963)

$$\omega_c = \frac{(k+q)^2}{2m} + \frac{q^2}{2m} \qquad \omega_c' = \frac{q^2}{2m} - \frac{qk_f}{2m}$$

Czyz and Gottfried proposed to replace the Fermi n(k) with that of an actual nucleus. (a) hard core gas; (b) finite system of noninteracting fermions; (c) actual large nucleus.





Short Range Correlations (SRCs)

Mean field contributions: $k < k_F$

Well understood, Spectroscopic Factors ≈ 0.65

High momentum tails: $k > k_F$

Calculable for few-body nuclei, nuclear matter.

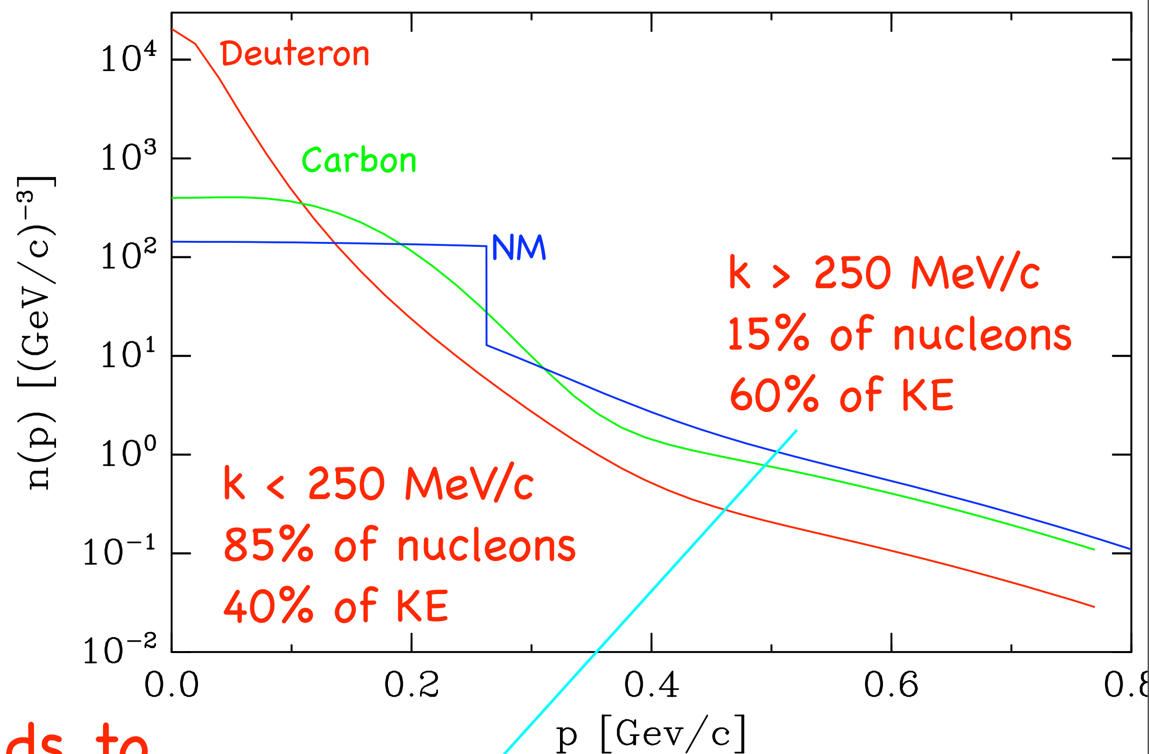
Dominated by two-nucleon short range correlations

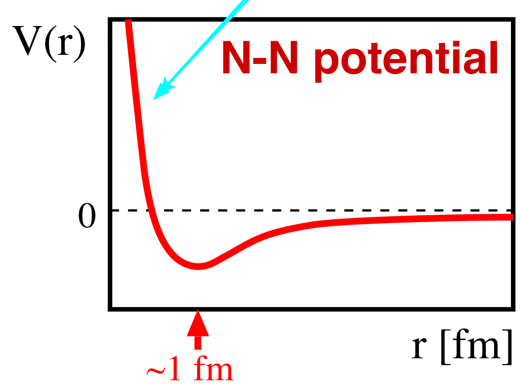
Poorly understood part of nuclear structure

Sign. fraction have $k > k_F$

Uncertainty in SR interaction leads to uncertainty at k>>, even for simplest systems

Isolate short range interactions (and SRC's) by probing at high p_m: (e,e'p) and (e,e')





Calculations of SRC

Show up at large momentum

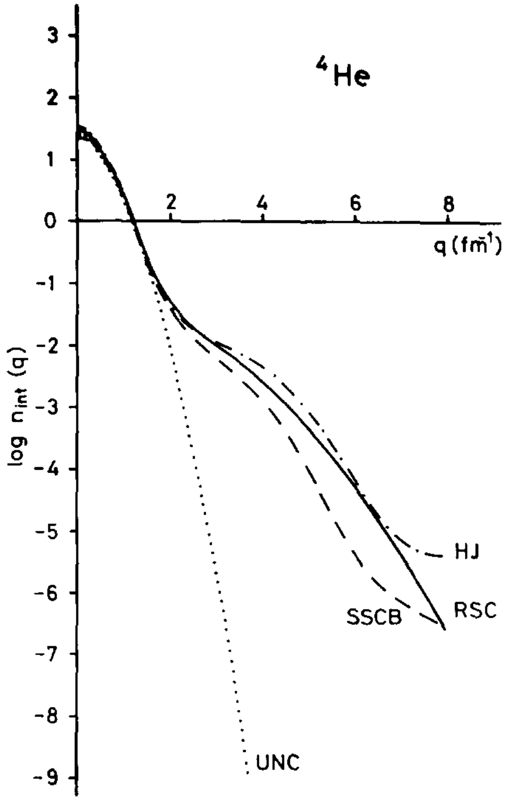


Fig. 2. Momentum distributions for ^{4}He, HJ: Hamada–Johnston potential, RSC: Reid soft core potential, SSCB: de Tourreil–Sprung super soft core potential B, UNC: uncorrelated, for the RSC potential. The other uncorrelated distributions do not differ appreciably for $q > 2$ fm^{-1}.

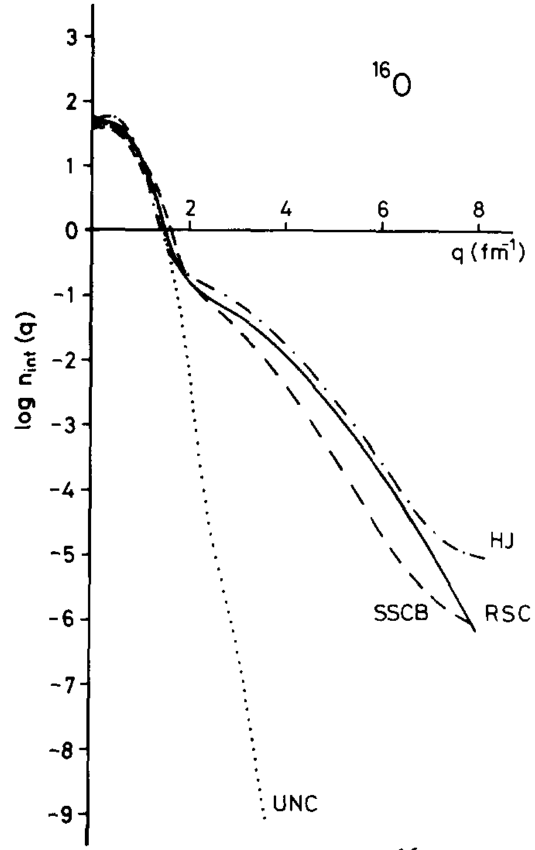
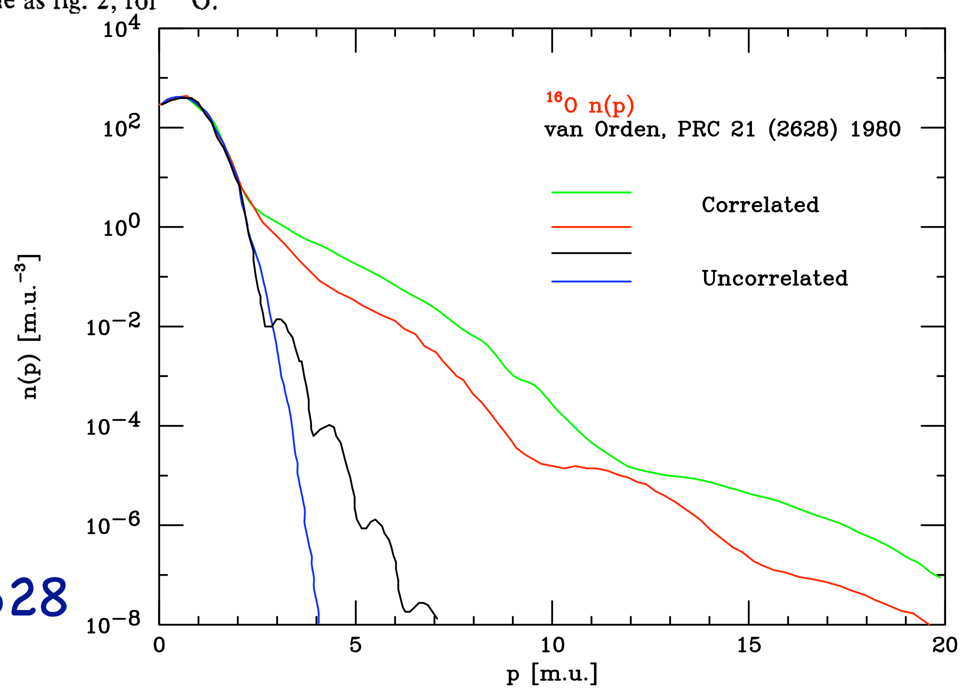


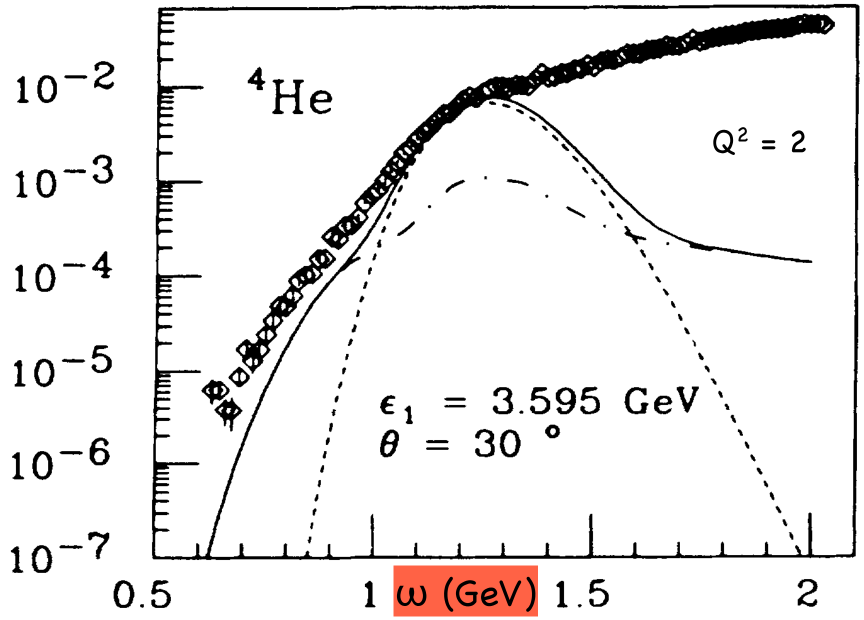
Fig. 3. Same as fig. 2, for ^{16}O.

Zabolitzky and Ey, PLB 76, 527

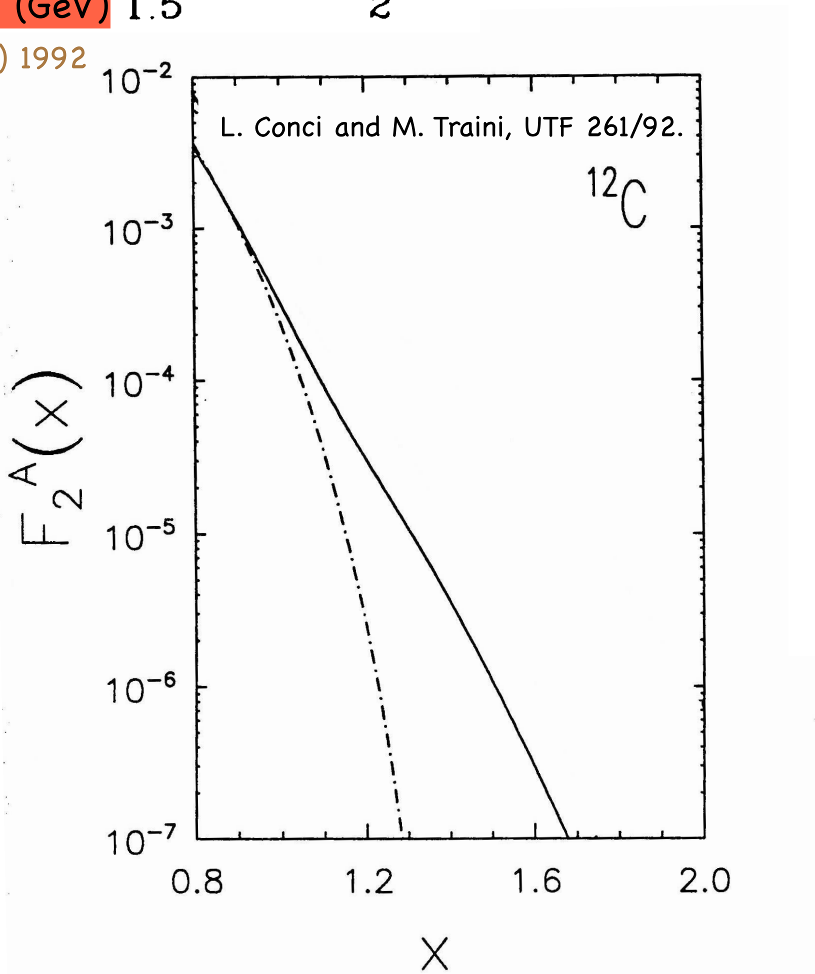


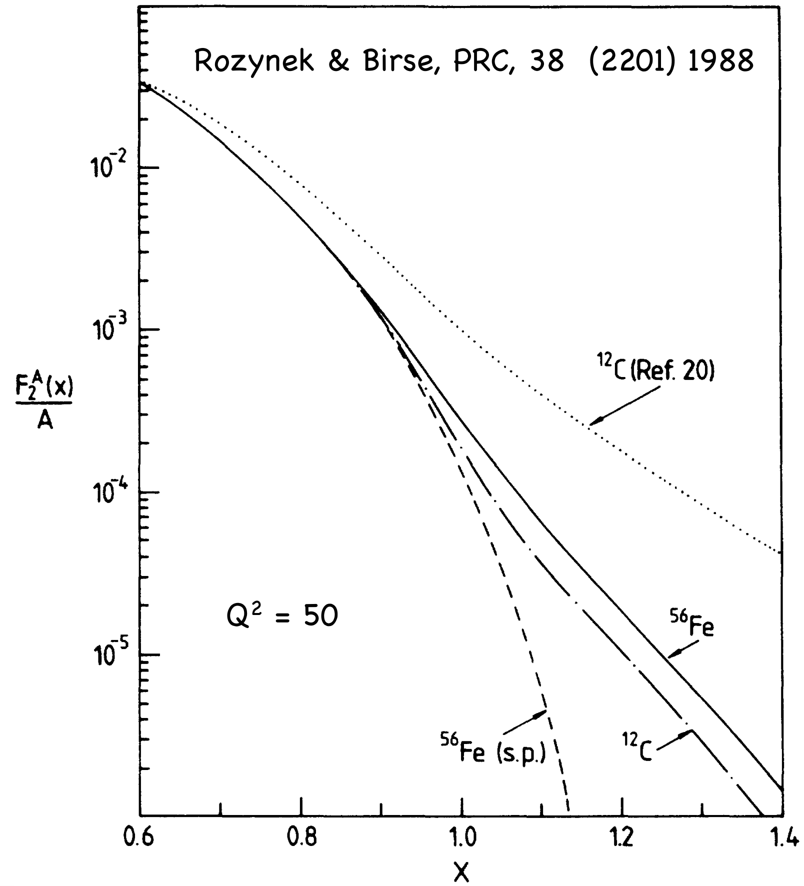
Van Orden et al., PRC21, 2628

Correlations are accessible in QES and DIS at large x (small energy loss)



CdA, Day, Liuti, PRC 46 (1045) 1992

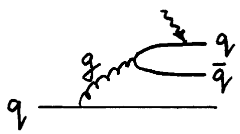


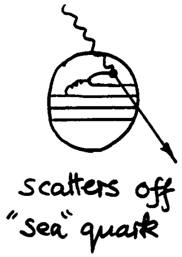


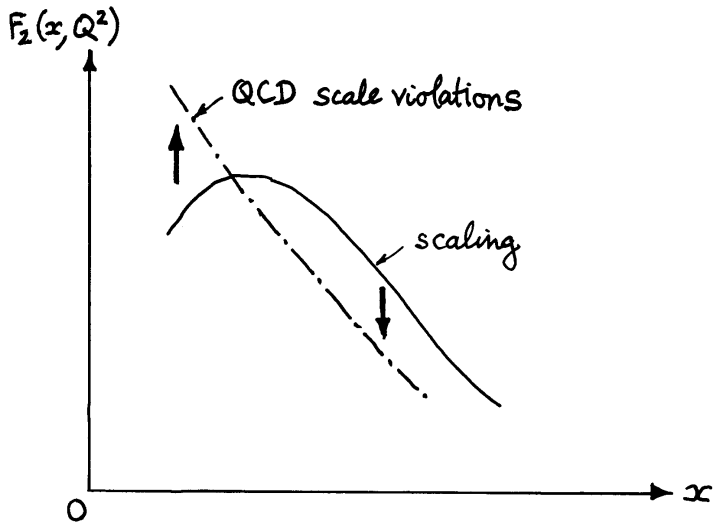
Scaling in DIS

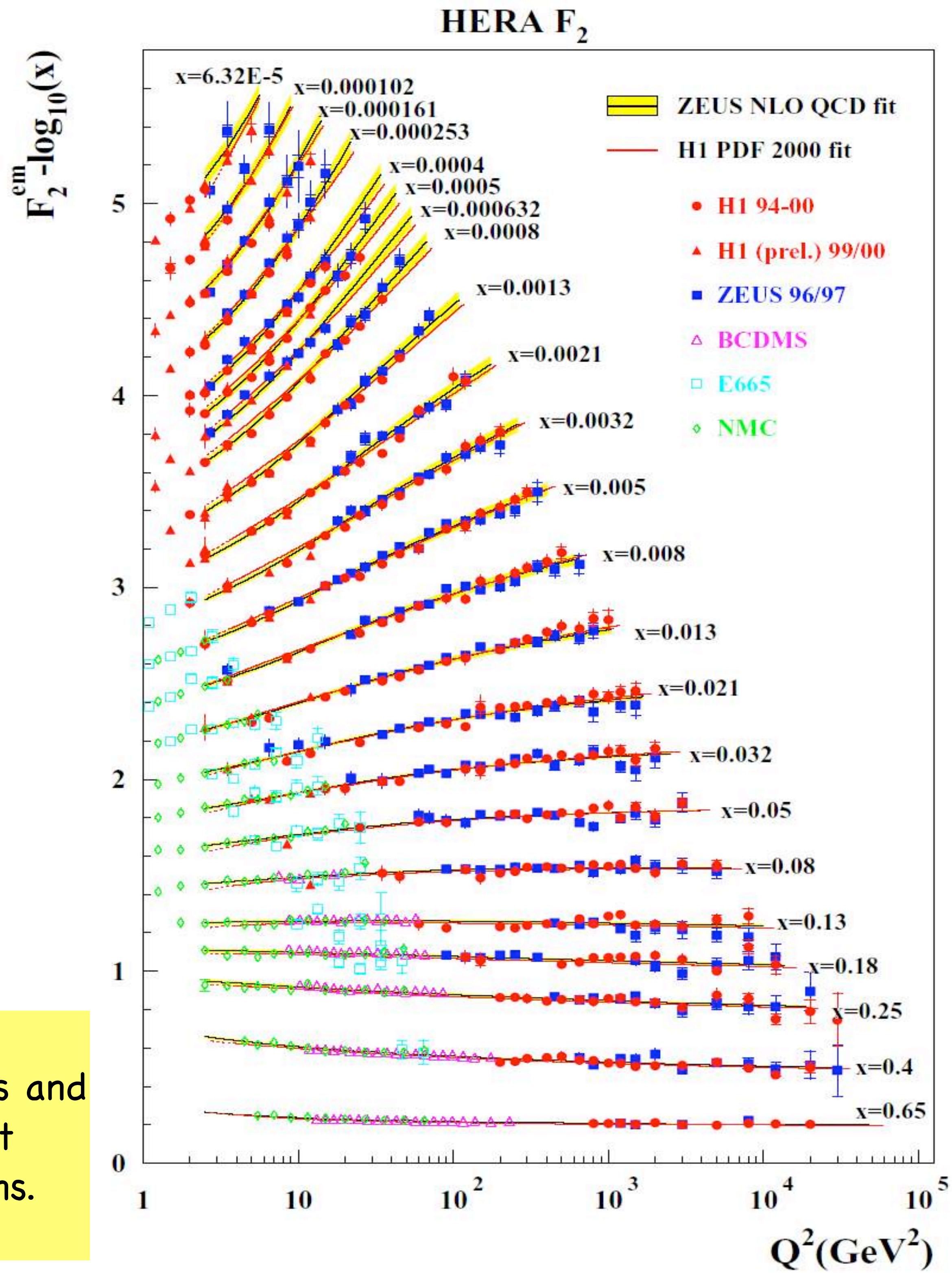
$$F_2(x, Q^2) \to F_2(x)$$

Existence of partons (quarks) revealed by DIS at SLAC in 1960's





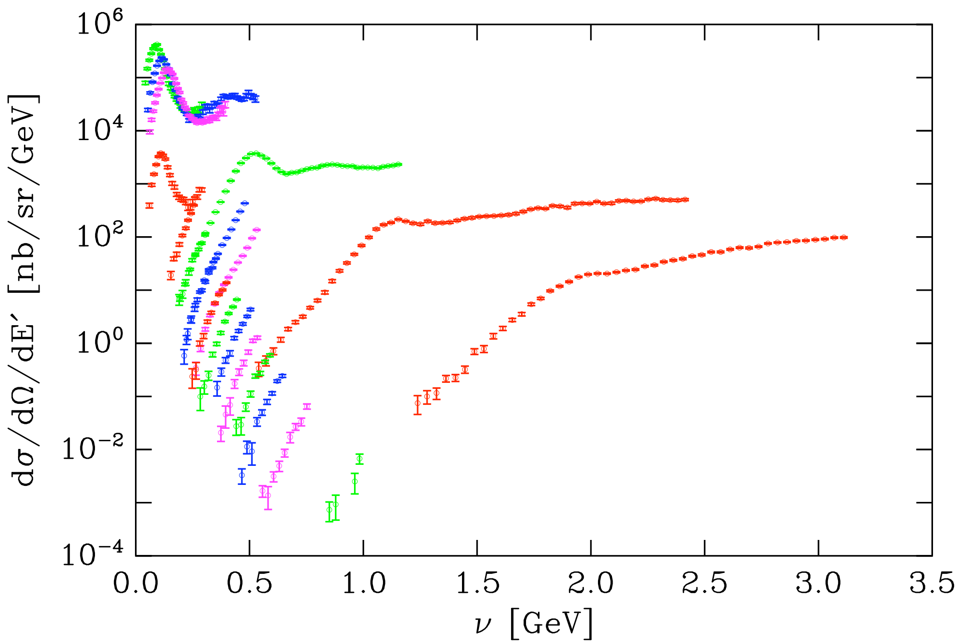


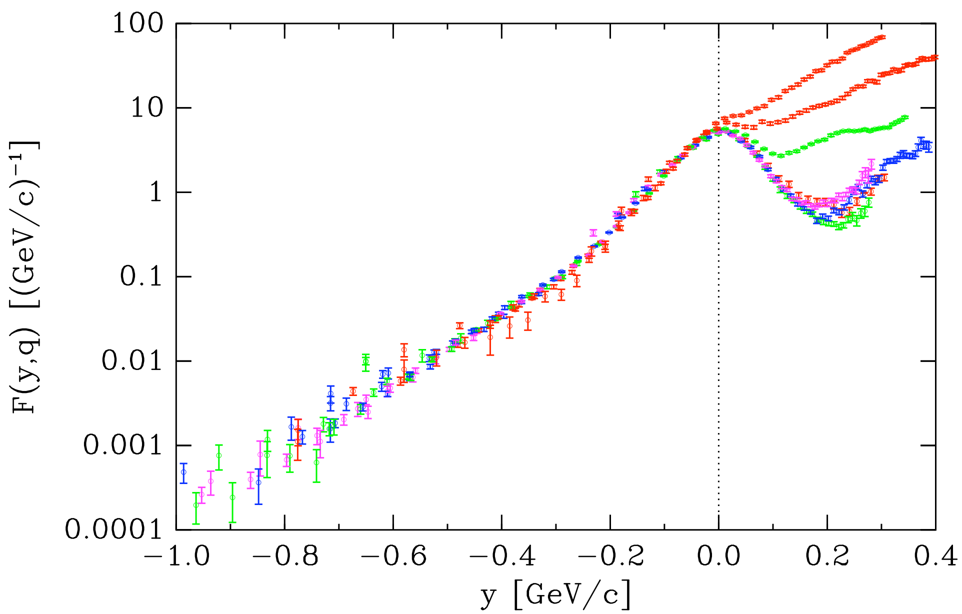


If the data scales then it validates the assumptions about the underlying physics and scale-breaking provides information about conditions that go beyond the assumptions.

Scaling in QES

At moderate Q^2 inclusive data from nuclei has been well described in terms y-scaling, one that arises from the assumption that the electron scatters from quasi-free nucleons. y is the momentum of the struck nucleon parallel to the momentum transfer: $y \approx -q/2 + m\nu/q$ y = 0 at quasielastic peak



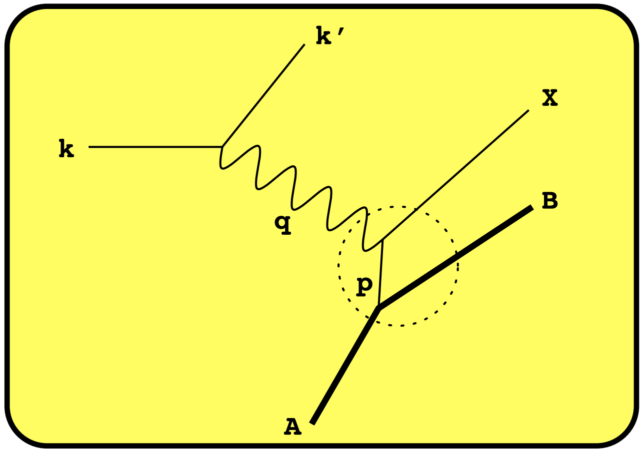


$$\boxed{F(y) = \frac{\sigma^{\exp}}{(Z\tilde{\sigma}_p + N\tilde{\sigma}_n)} \cdot K}$$

$$\boxed{n(k) = -\frac{1}{2\pi y}\frac{dF(y)}{dy}}$$

We expect that as Q^2 increases we should see for evidence (x-scaling) that we are scattering from a quark that has obtained its momenta from interactions with partons in other nucleons. These are super-fast quarks.

y-scaling in PWIA



$$\frac{d^2\sigma}{dEd\Omega_{e'}} = \sum_{i=1}^{A}\int d\vec{k}\int dE_s\,\sigma_{ei}\,S_i(E_s,k)$$
$$\times\,\delta(\omega - E_s + M_A - (M^2+\vec{k'}^{\,2})^{1/2} - (M_{A-1}^2+\vec{k}^2)^{1/2}),$$

$$\frac{d^2\sigma}{dEd\Omega_{e'}} = 2\pi\sum_{i=1}^{A}\int_{E_{min}}^{E_{max}} dE_s\int_{k_{min}}^{k_{max}} dk\,k\,\overline{\sigma}_{ei}\,S_i(E_s,k)\;\underbrace{k\left(\left|\frac{\partial\omega}{\partial\cos\theta_{kq}}\right|\right)^{-1}}_{K}$$

$$\sigma_{ei} = f(q,\omega,\vec{k},E_s)$$

$$E_{min} = M_{A-1} + M - M_A,\;\; E_{max} = M_A^* - M_A \qquad K = q/(M^2+(\vec{k}+\vec{q})^2)^{1/2}$$

$$M_A^* = [(\omega+M_A)^2 - q^2]^{1/2}$$

k_{min} and k_{max} are determined from $\cos\theta = \pm 1$

$$\omega - E_s + M_A = (M^2+q^2+k^2\pm 2kq)^{1/2} + (M_{A-1}^2+k^2)^{1/2}$$

y-scaling in PWIA

- lower limit becomes y= y(q,ω)
- upper limits grows with q and because momentum distributions are steeply peaked, can be replaced with ∞
- Assume $S(E_s,k)$ is isospin independent and neglect E_s dependence of σ_{ei} and kinematic factor K and pull outside
- At very large q and ω, we can let $E_{max}= \infty$, and integral over E_s can be done

$$n(k) = \int S(E_s, k)\, dE_s$$

Now we can write

$$\boxed{\frac{d^2\sigma}{dEd\Omega_{e'}} = (Z\overline{\sigma}'_{ep} + N\overline{\sigma}'_{en})K'F(y)}$$

where

$$F(y) = 2\pi \int_{|y|}^{\infty} n(k)kdk$$

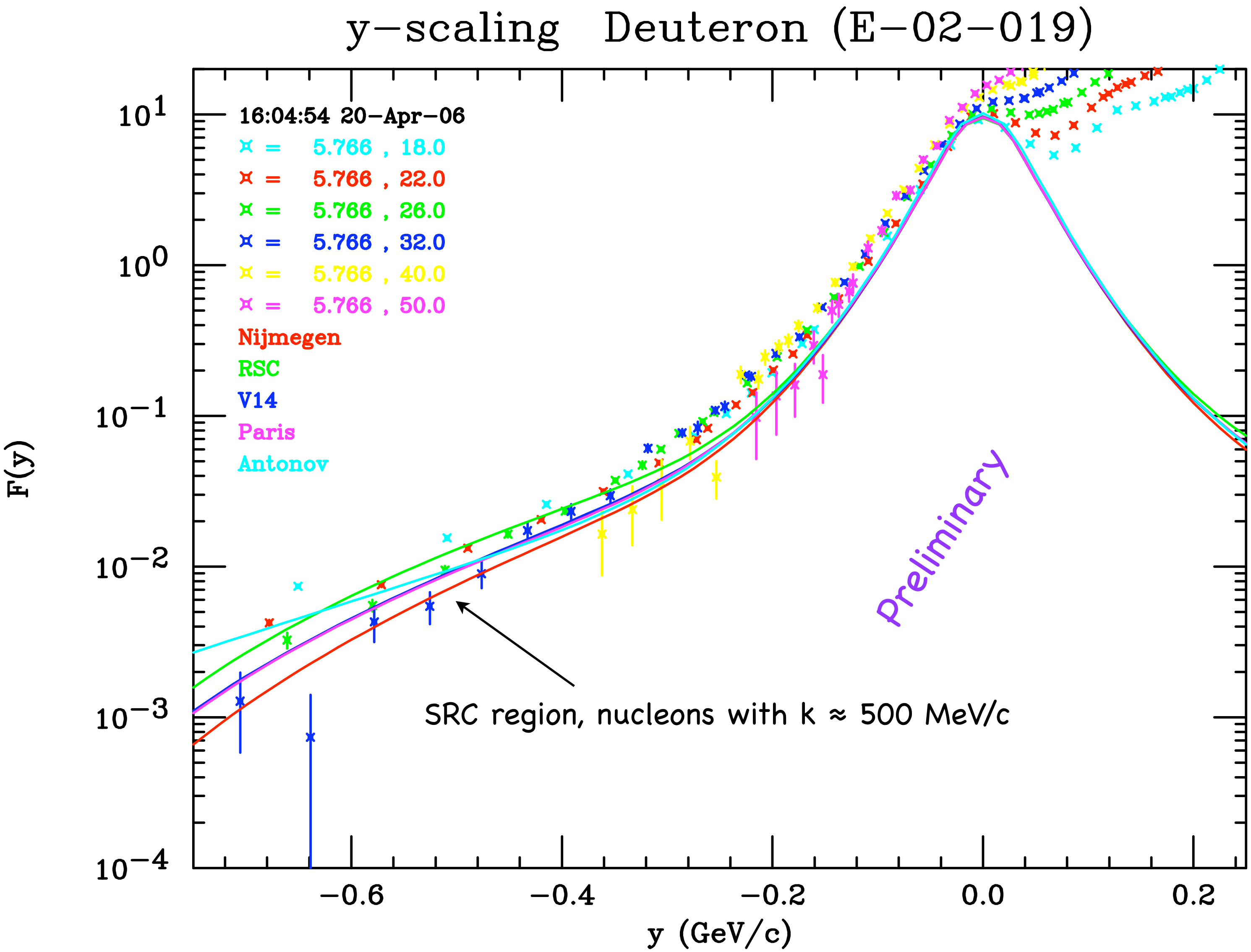
Scaling (independent of Q^2) of QES provides direct access to momentum distribution

Assumptions

- No FSI
- No internal excitation of (A-1)
- Full strength of Spectral function can be integrated over at finite q
- No inelastic processes
- No medium modifications

Potential scale breaking mechanisms

Can y-scaling provide direct access to n(k)?



Deuteron F(y) and calculations based on NN potentials

S(k,E=2.2MeV) = n(k)

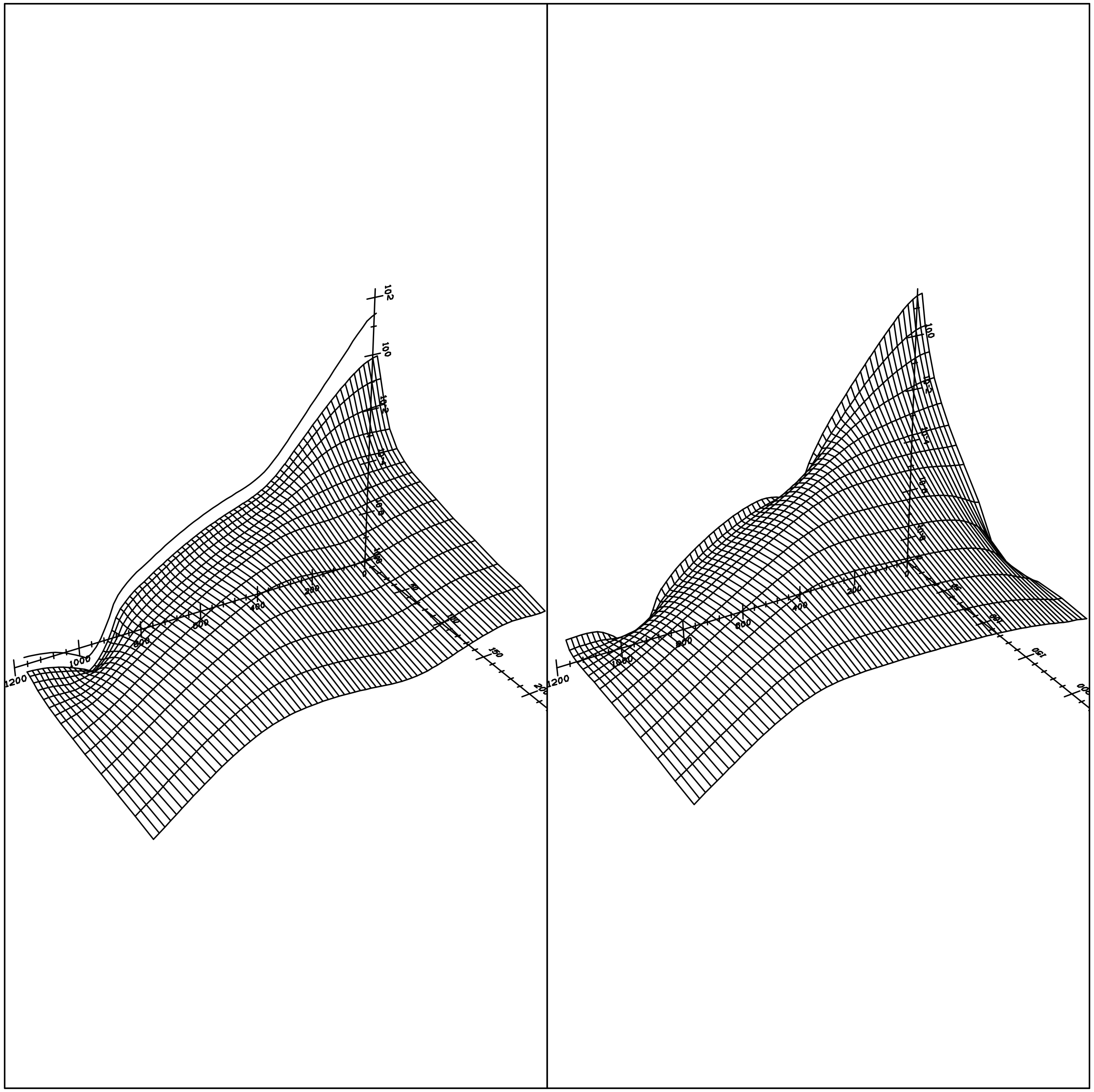
$$F(y) = \frac{\sigma^{exp}}{(Z\sigma_p + N\sigma_n)} \cdot K$$

$$n(k) = -\frac{1}{2\pi y}\frac{dF(y)}{dy}$$

Assumption: scattering takes place from a quasi-free proton or neutron in the nucleus.

y is the momentum of the struck nucleon parallel to the momentum transfer: $y \approx -q/2 + m\nu/q$

Helium-3

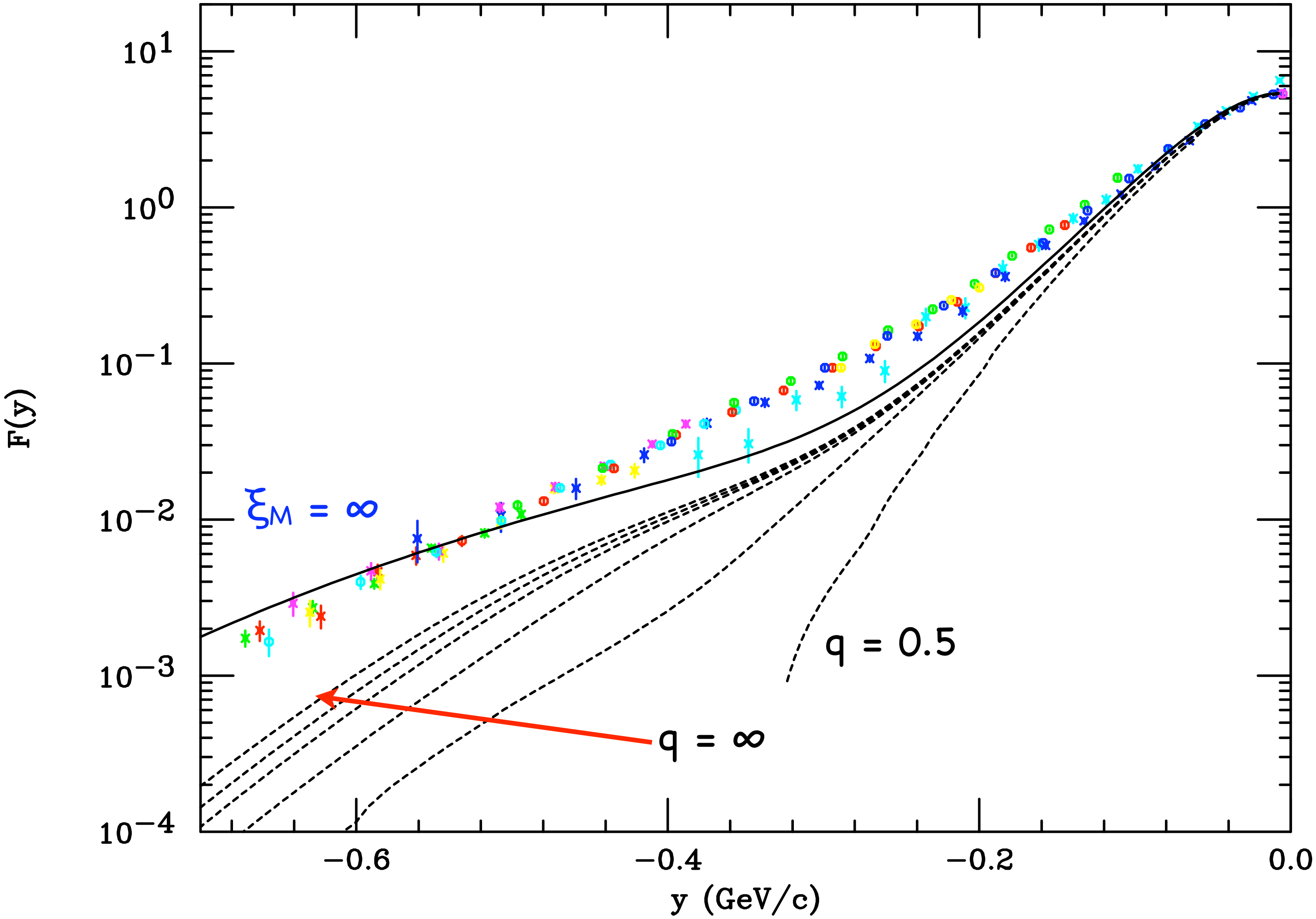


Hanover group, $T = 0$ and $T = 1$ pieces (right)

In nuclei the distribution of the strength in energy complicates the relationship between the scaling function and n(k).

The spectral function S(k,E) for ^3He

Theoretical ^3He F(y) integrated at increasing q



Is the energy distribution as calculated (scaling occurs at much lower q)?

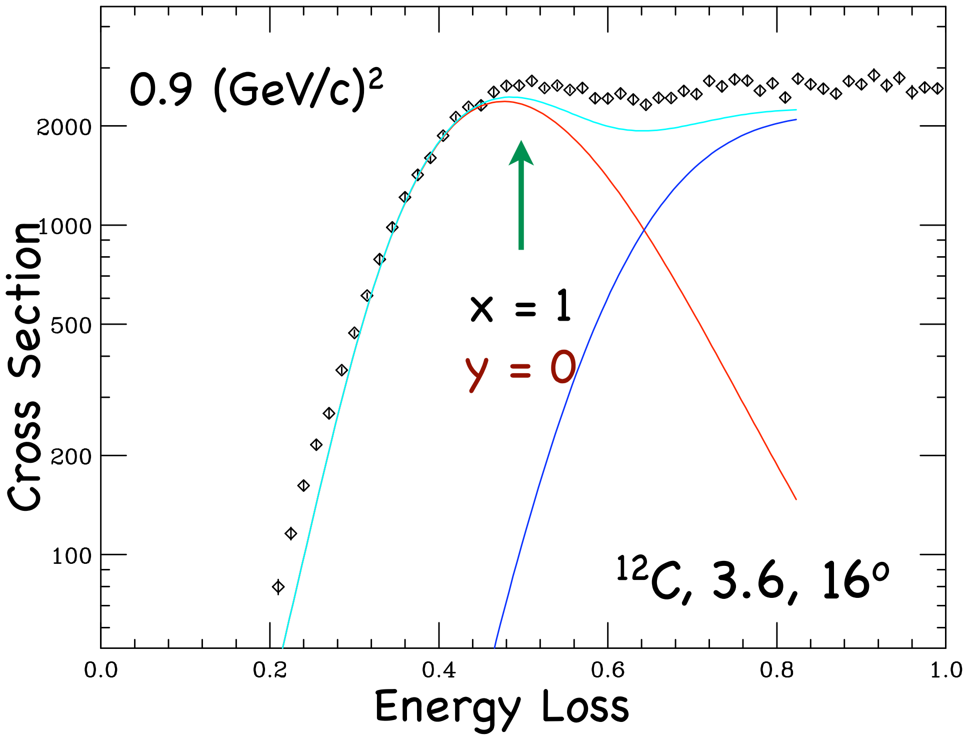
Do other processes play a role?

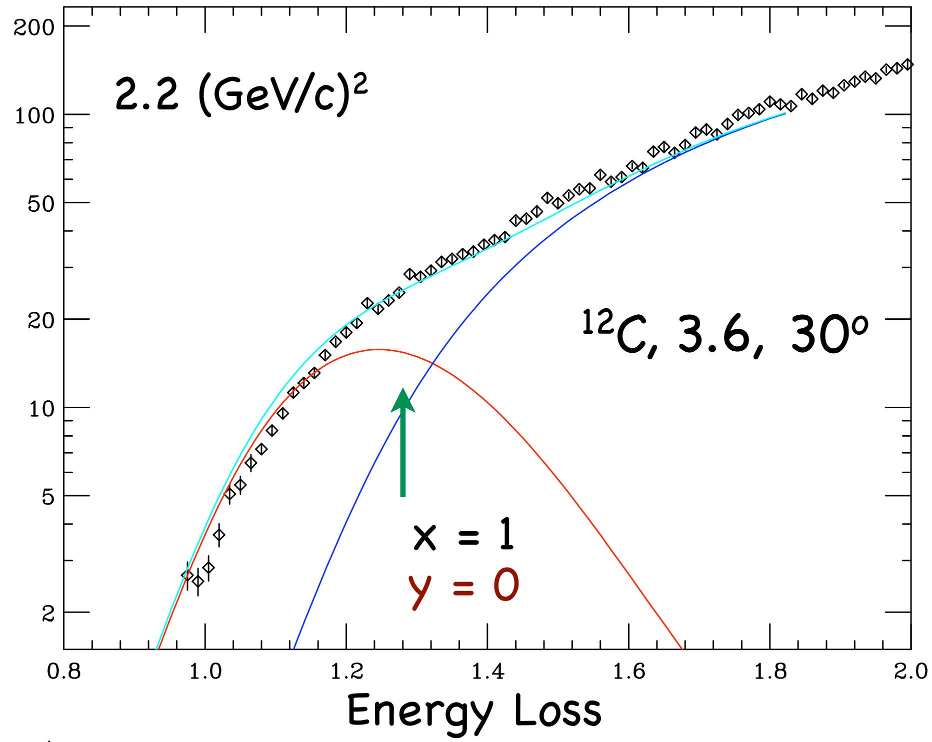
FSI or/and DIS

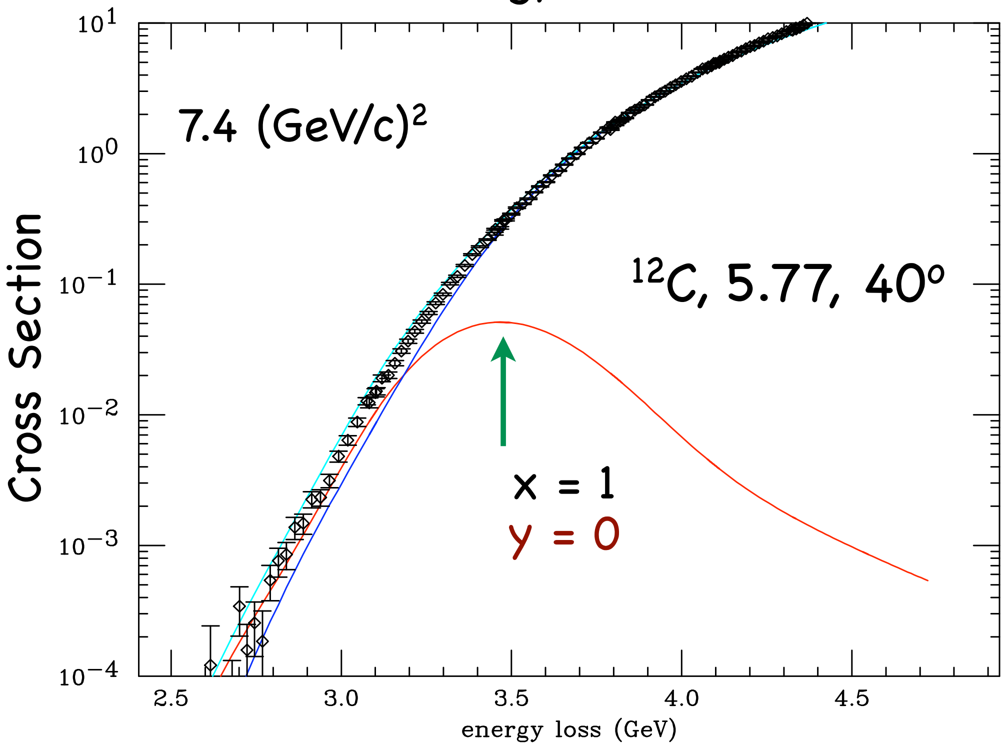
distribution of strength?

As q increases, more and more of the spectral function S(k,E) is integrated.

Inelastic contribution increases with Q^2

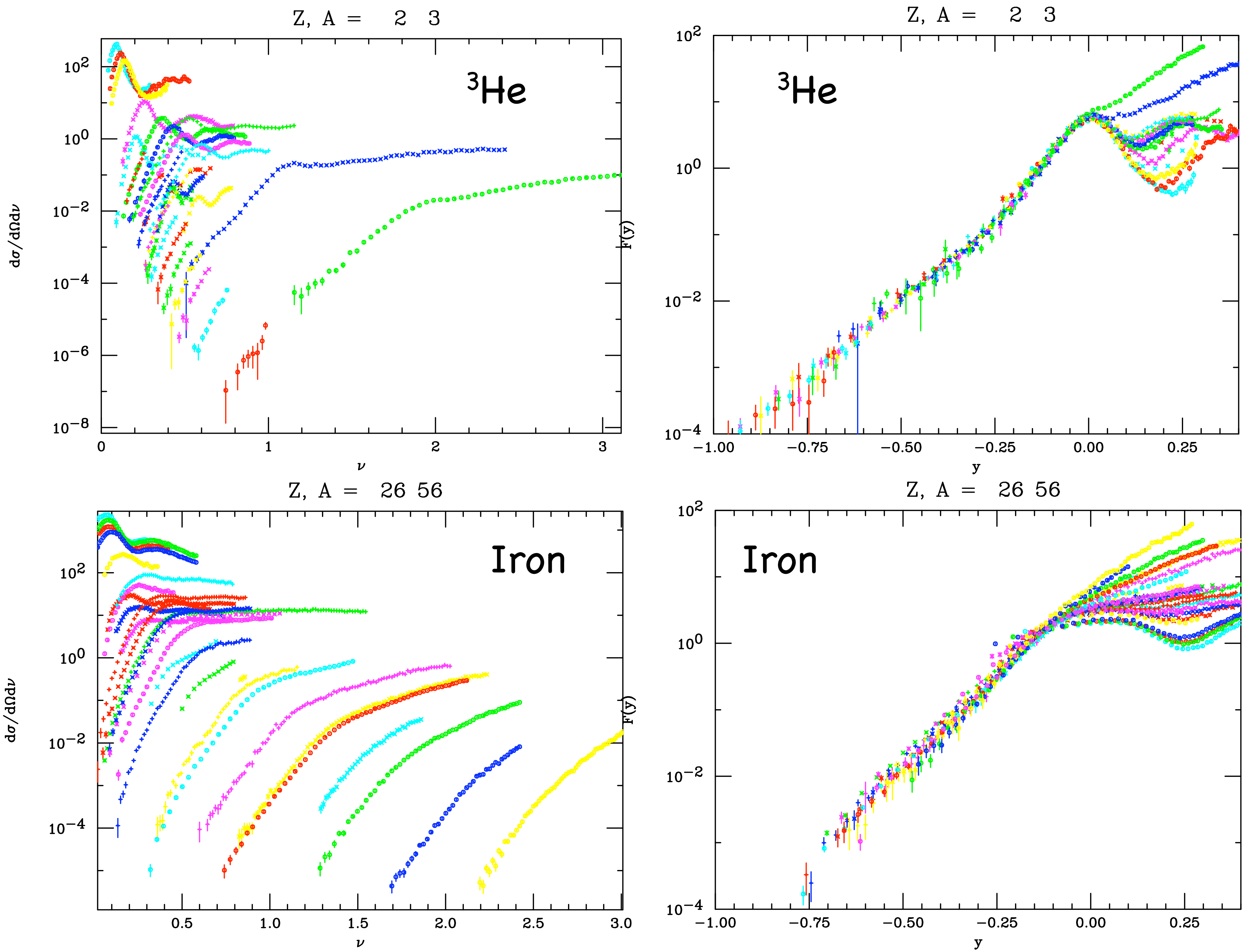






DIS begins to contribute at $x > 1$, $y < 0$

Convolution model


Z, A = 2 3
^{3}He
$d\sigma/d\Omega d\nu$
ν
F(y)
y
Z, A = 26 56
Iron

Scaling of the response function shows up in a variety of disciplines. Scaling in inclusive neutron scattering from atoms provides access to the momentum distributions.

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Scaling and final-state interactions in deep-inelastic neutron scattering

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(Received 20 January 1984)

The momentum distributions of atoms in condensed matter can be determined by neutron inelastic scattering experiments if the momentum transfer $\hbar q$ is large enough for the scattering to be described by the impulse approximation. This is strictly true only in the limit $q \to \infty$ and, in practice, the experimentally determined momentum distributions are distorted by final-state interactions by an amount that is typically 2% to 8%. In this paper we develop a self-consistent method for correcting for the effect of these final-state-interaction effects. We also discuss the Bjorken-scaling and y-scaling properties of the thermal-neutron scattering cross section and demonstrate, in particular, the usefulness of y scaling as an experimental test for the presence of residual final-state interactions.

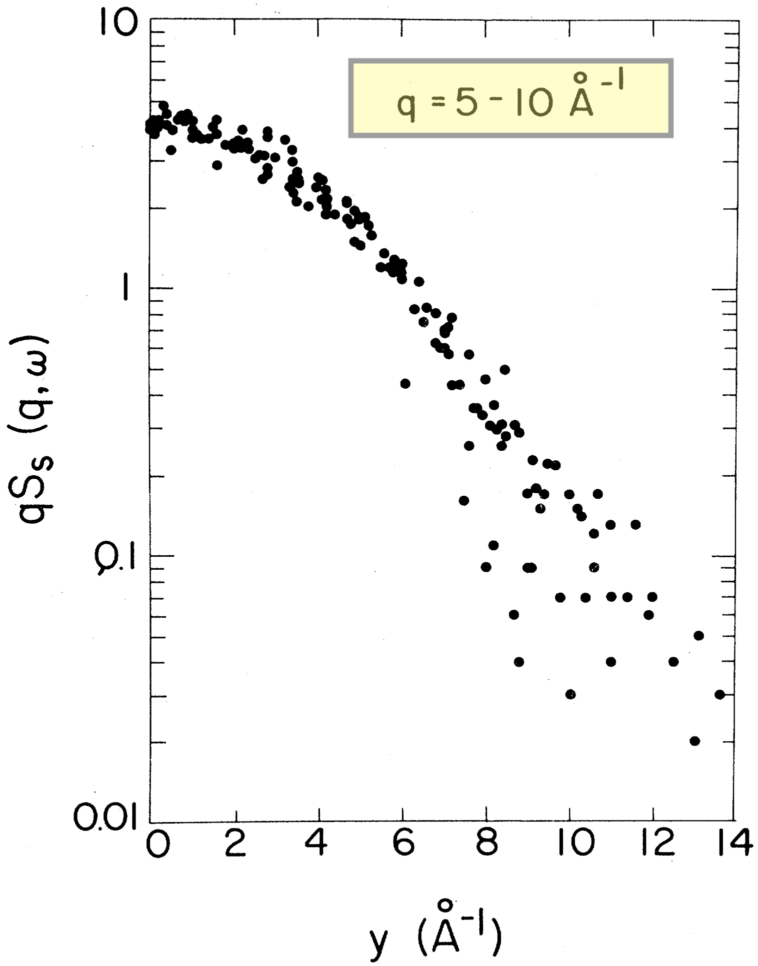


FIG. 1. y scaling in liquid neon. $qS_s(q,\omega)$ is shown in arbitrary units as a function of $y=(m/\hbar q)(\omega-\omega_r)$ for liquid neon at $T=26.9$ K for the eleven values of q in the range 5.0–10.0 Å^{-1}, which were used in the determination of the momentum distribution in Ref. 7. The data are from Ref. 59.

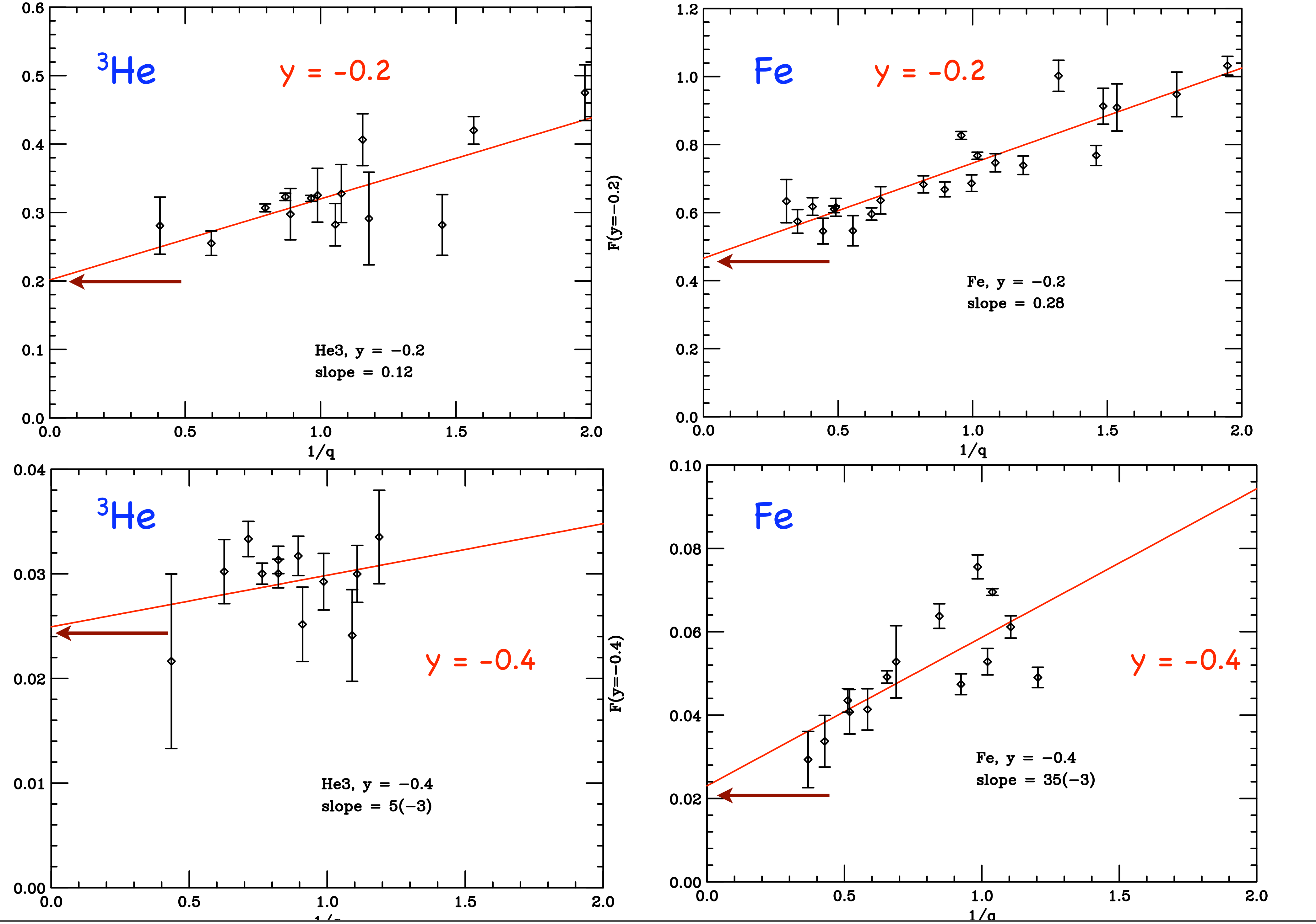
Momentum distributions are "distorted" by the presence of FSI

y-scaling as a test for presence of FSI

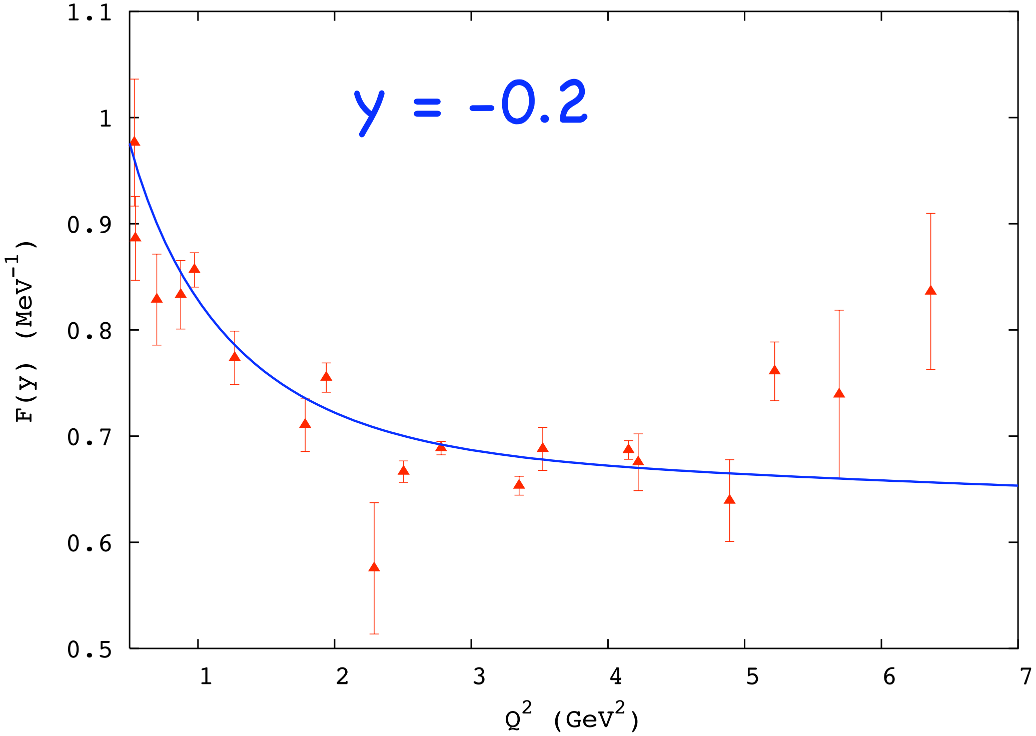
FSI have a 1/q dependence

Weinstein & Negele PRL 49 1016 (1982)

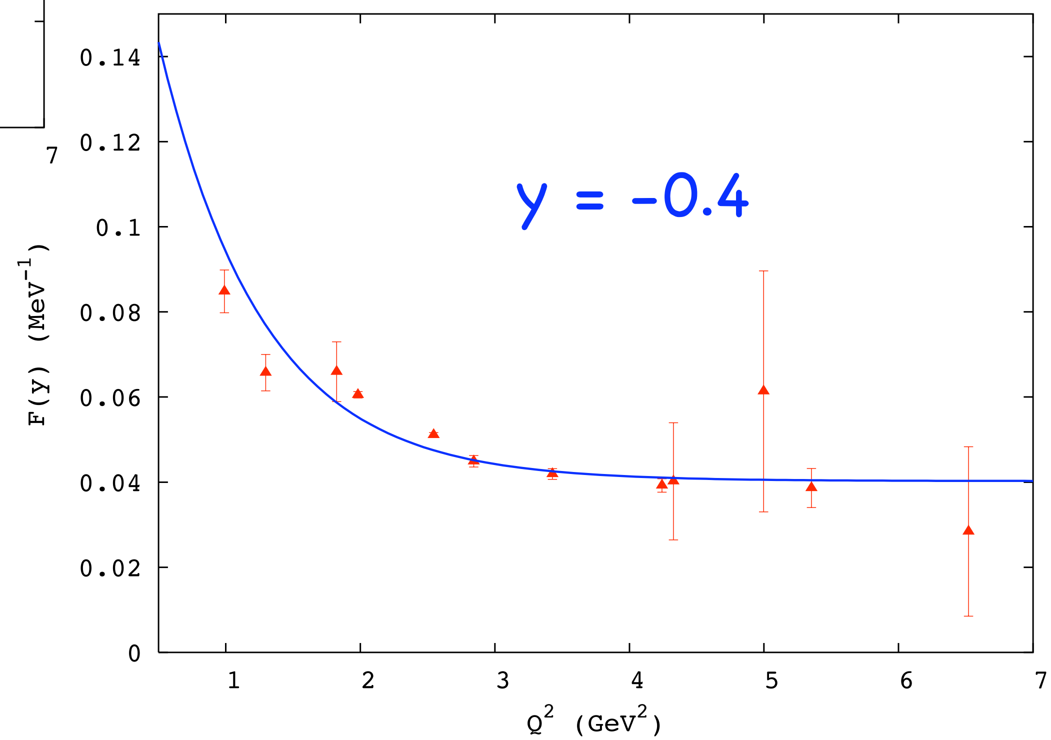
Convergence of F(y,q)



Convergence of F(y,q)



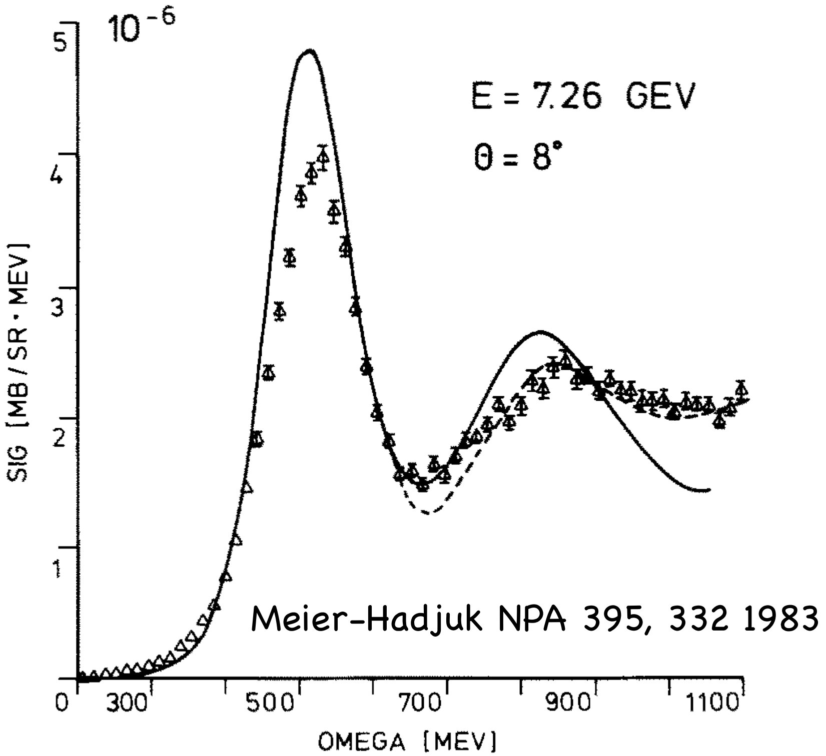
^{12}C

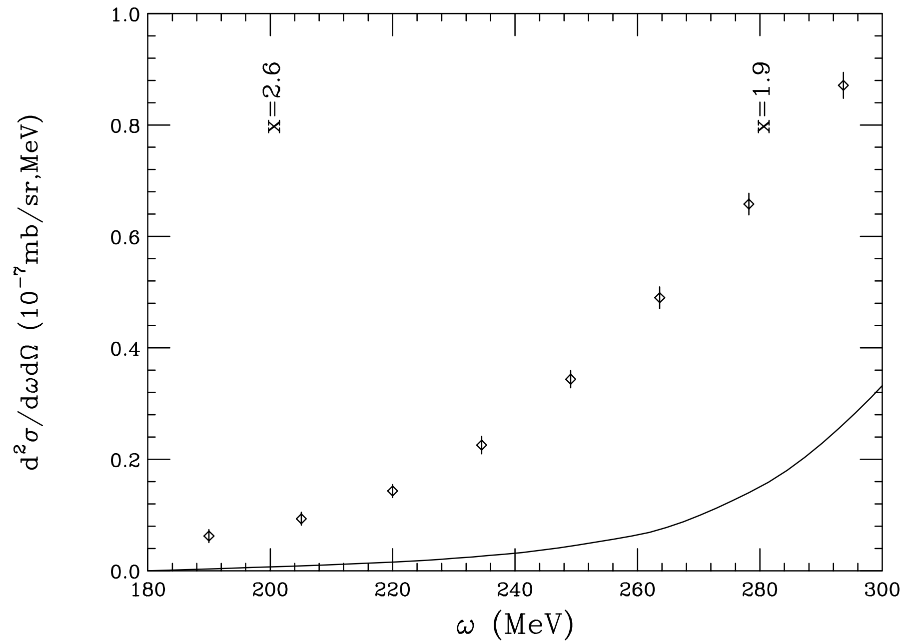


Final State Interactions

In (e,e′p) flux of outgoing protons strongly suppressed: 20-40% in C, 50-70% in Au

In (e,e′) the failure of IA calculations to explain dσ at small energy loss



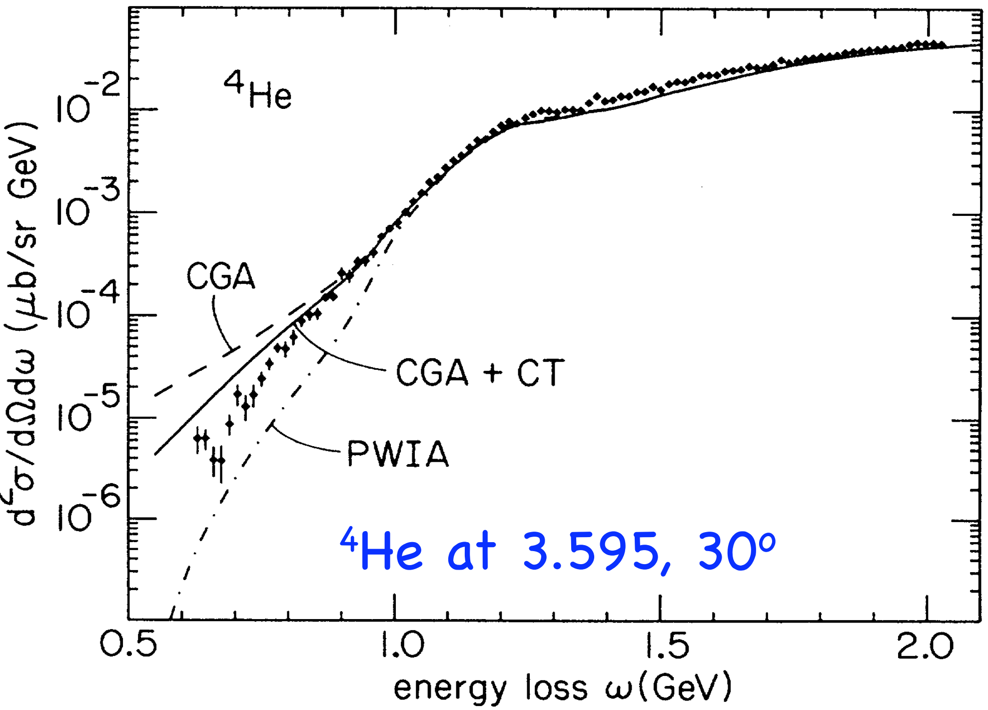


FSI has two effects: energy shift and a redistribution of strength from QEP to the tails, just where correlation effects contribute.

Benhar et al uses approach based on NMBT and Correlated Glauber Approximation

Ciofi degli Atti and Simula use GRS 1/q expansion and model spectral function

Final State Interactions in CGA



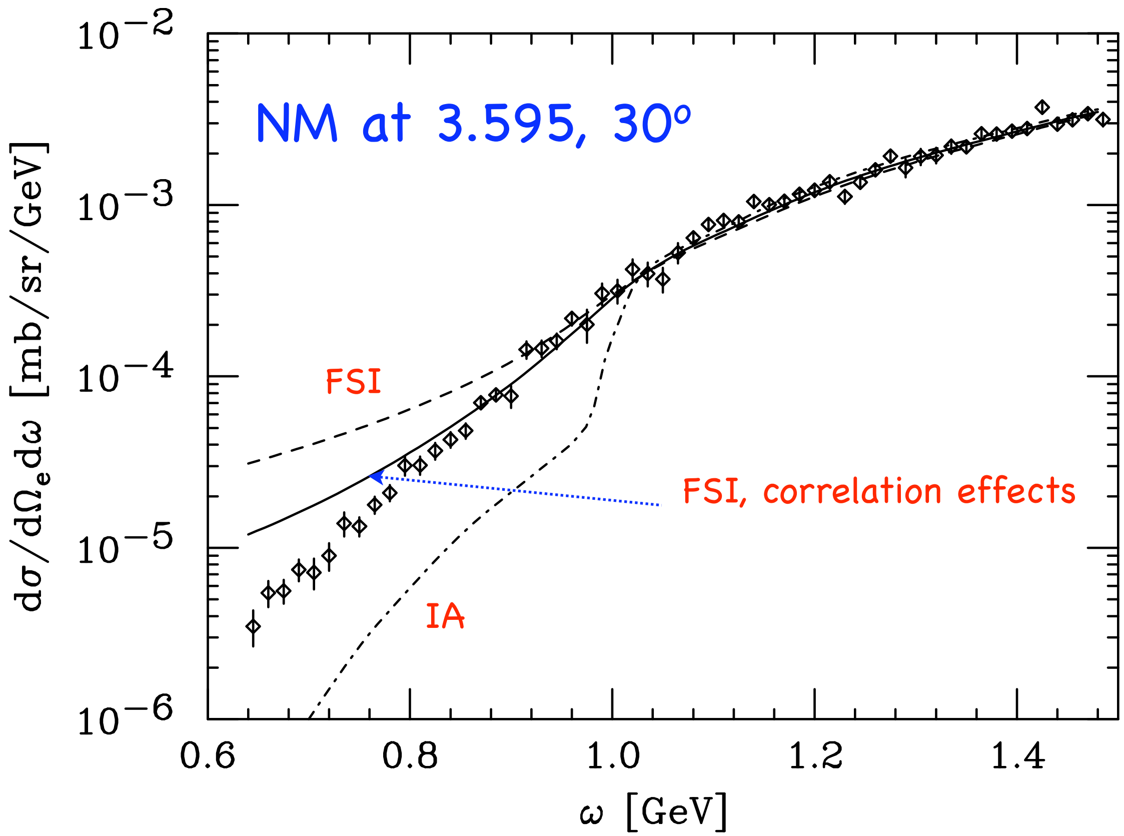
Benhar et al. PRC 44, 2328

Benhar, Pandharipande, PRC 47, 2218

Benhar et al. PLB 3443, 47

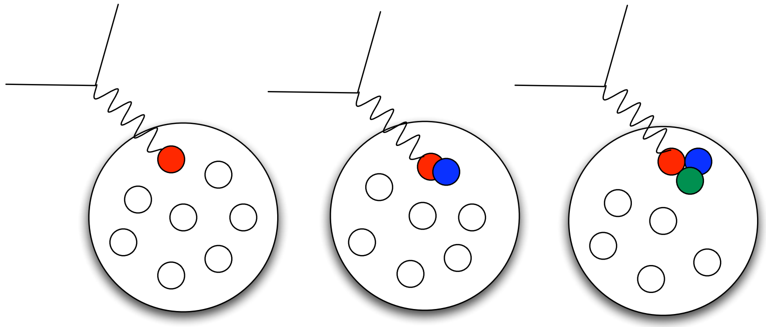
CGA over estimates the FSI

Modifications of the free space NN scattering amplitude in the medium?



CS Ratios and SRC

In the region where correlations should dominate, large x,



$$\sigma(x,Q^2) = \sum_{j=1}^{A} A\frac{1}{j}a_j(A)\sigma_j(x,Q^2)$$
$$= \frac{A}{2}a_2(A)\sigma_2(x,Q^2) + \frac{A}{3}a_3(A)\sigma_3(x,Q^2) + \vdots$$

$a_j(A)$ are proportional to finding a nucleon in a j-nucleon correlation. It should fall rapidly with j as nuclei are dilute.

$$\sigma_2(x,Q^2) = \sigma_{eD}(x,Q^2) \text{ and } \sigma_j(x,Q^2) = 0 \text{ for } x > j.$$

$$\Rightarrow \quad \frac{2}{A}\frac{\sigma_A(x,Q^2)}{\sigma_D(x,Q^2)} = a_2(A)\Big|_{1<x\leq 2}$$

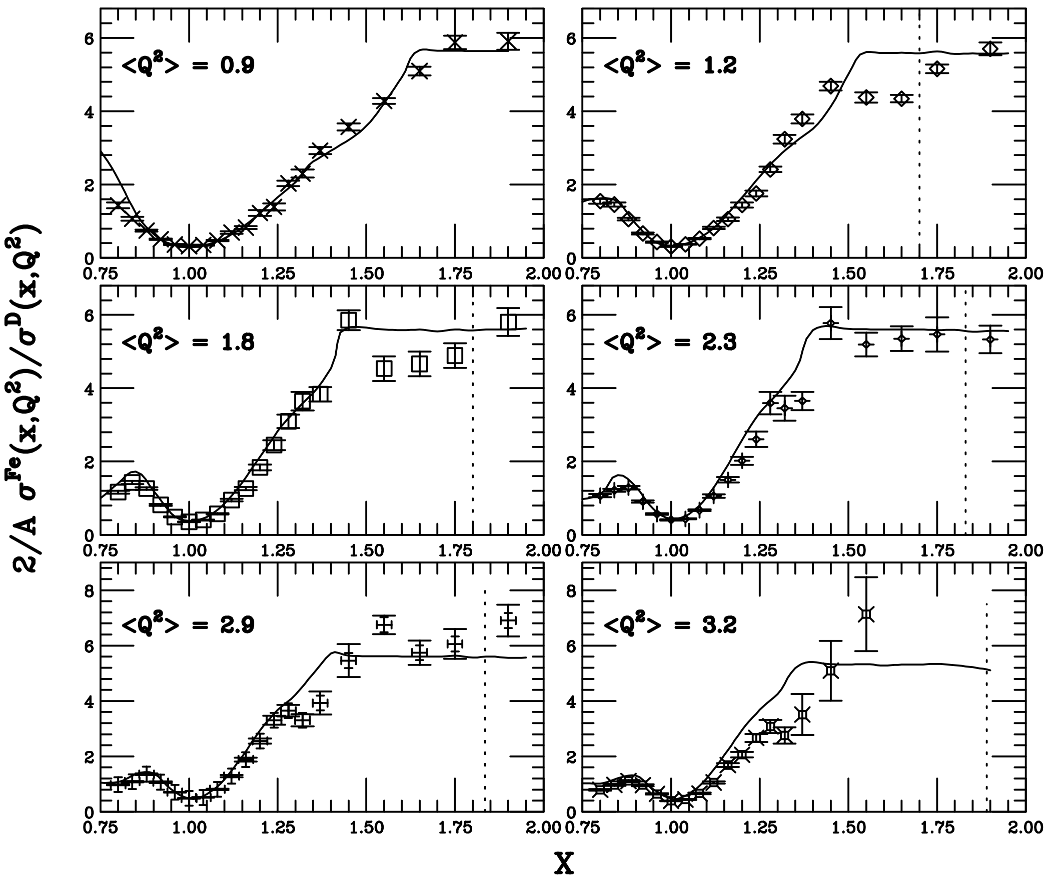
$$\frac{3}{A}\frac{\sigma_A(x,Q^2)}{\sigma_{A=3}(x,Q^2)} = a_3(A)\Big|_{2<x\leq 3}$$

In the ratios, off-shell effects and FSI largely cancel.

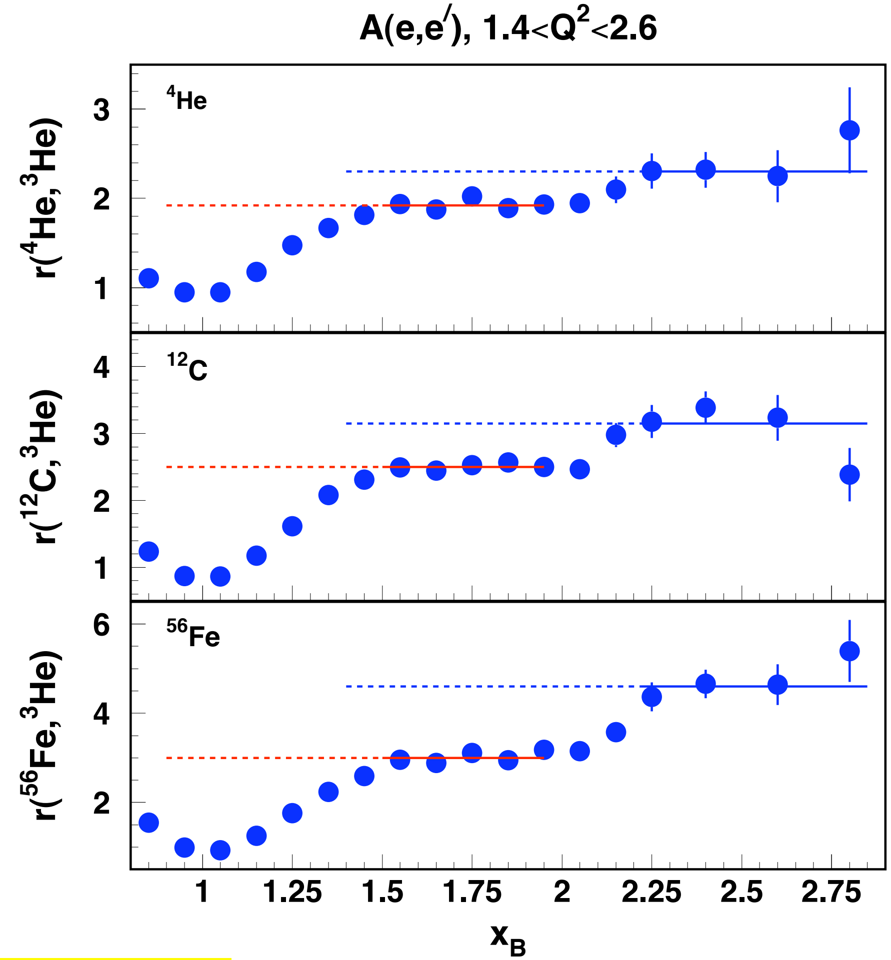
$a_j(A)$ is proportional to probability of finding a j-nucleon correlation

Ratios and SRC

$$\frac{2}{A}\frac{\sigma_A}{\sigma_D} = a_2(A); \quad (1.4 < x < 2.0)$$



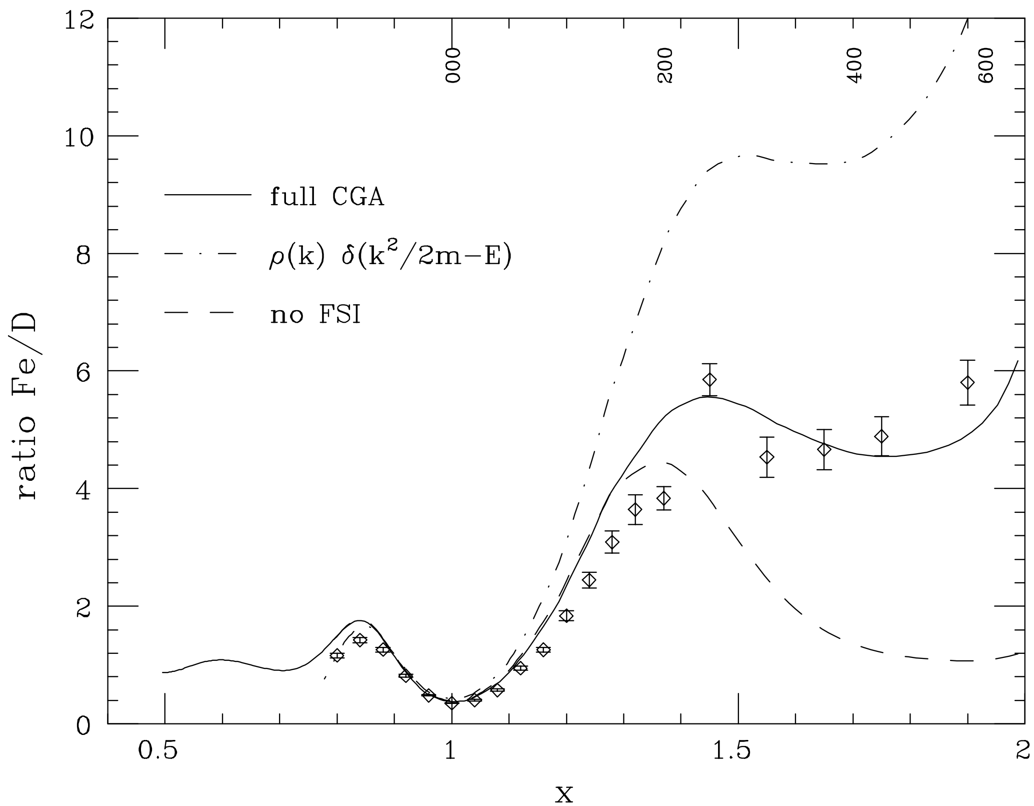
FSDS, Phys.Rev.C48:2451-2461,1993



$a_j(A)$ is proportional to probability of finding a j-nucleon correlation

$\alpha_{2N} \approx 20\%$
$\alpha_{3N} \approx 1\%$

CLAS data
Egiyan et al., PRL 96, 082501, 2006



Arguments about role of FSI

Benhar et al.: FSI includes a piece that has a weak Q^2 dependence, Benhar et al. PLB 3443, 47

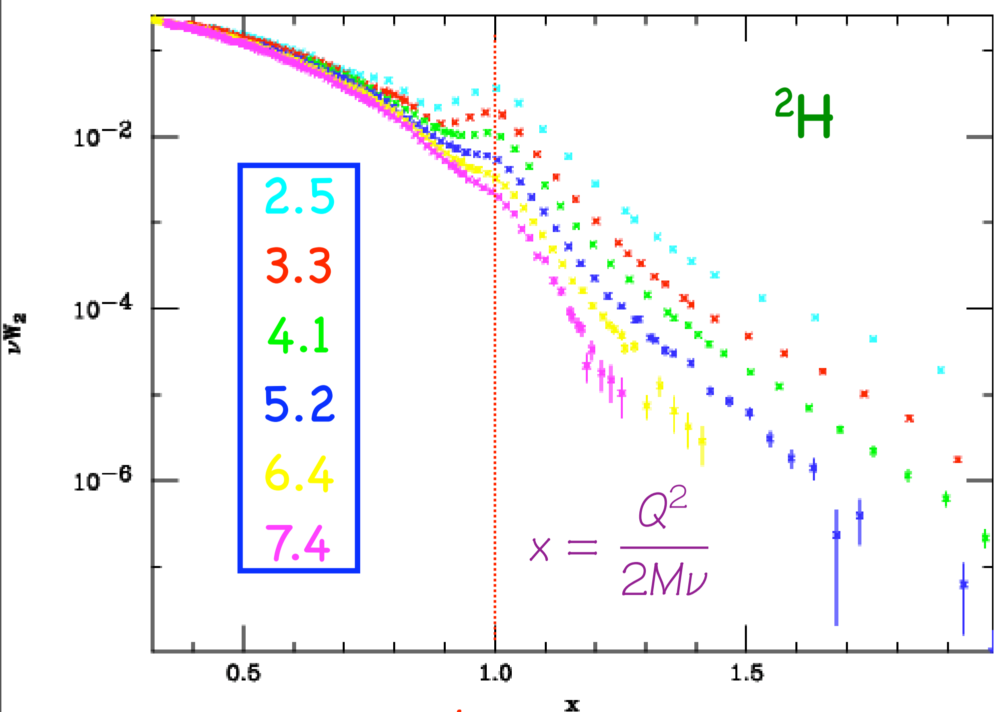
There is the cancellation of two large factors (≈ 3) that bring the theory to describe the data. These factors are Q^2 and A dependent

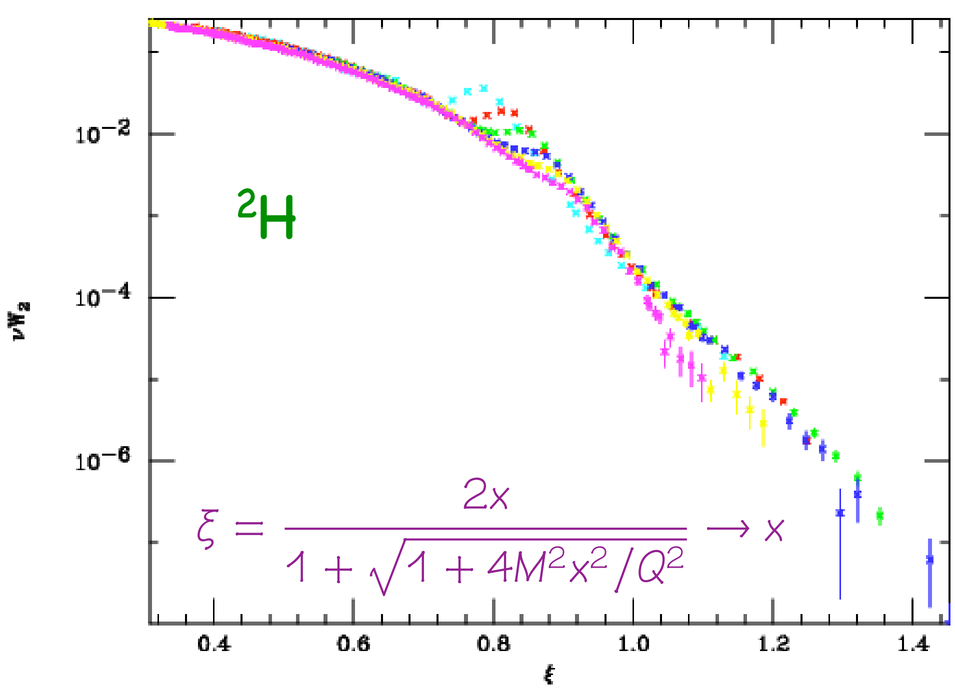
The solution

- Direct ratios to ^{2}H, ^{3}He, ^{4}He out to large x and over wide range of Q^2
  - Study Q^2, A dependence (FSI)
- Absolute Cross section to test exact calculations and FSI
- Extrapolation to NM

x and ξ scaling

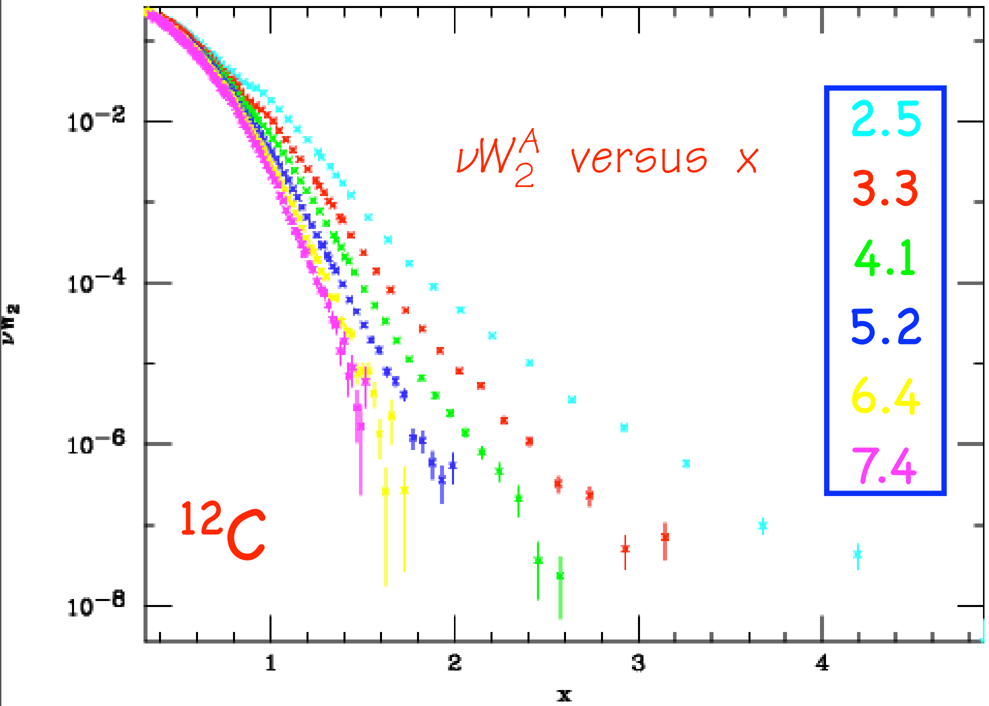
An alternative view is suggested when the data (deuteron) is presented in terms of scattering from individual quarks





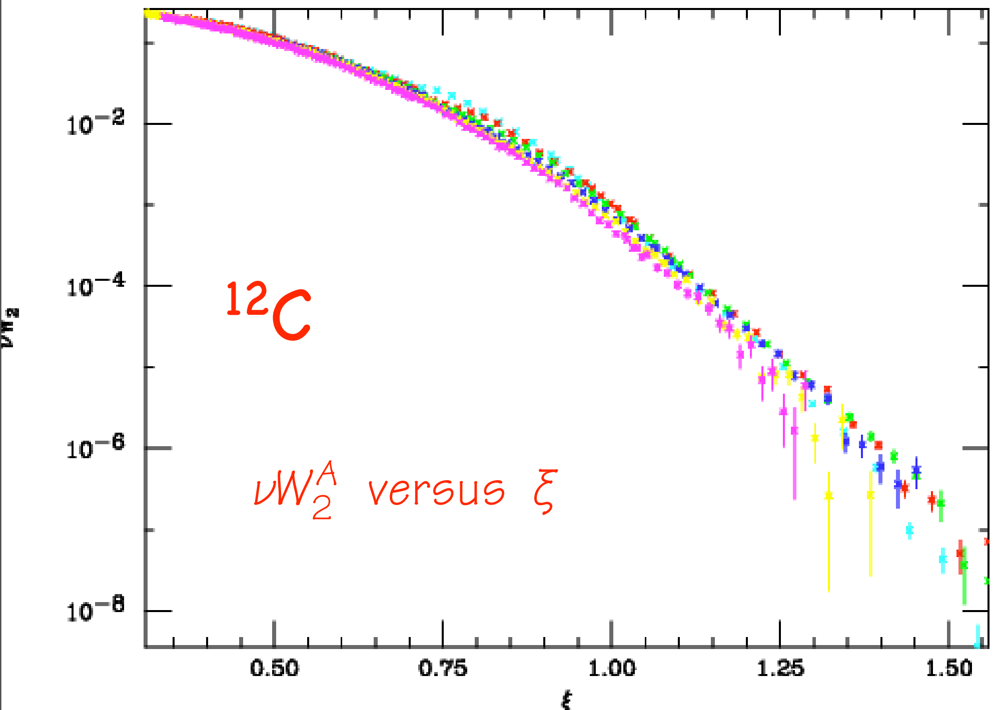
νW_2^A versus x $\qquad$ νW_2^A versus ξ

$$\nu W_2^A = \nu \cdot \frac{\sigma^{exp}}{\sigma_M}\left[1 + 2\tan^2(\theta/2)\cdot\left(\frac{1+\nu^2/Q^2}{1+R}\right)\right]^{-1}$$



The Nachtmann variable (fraction ξ of nucleon light cone momentum p^+) has been shown to be the variable in which logarithmic violations of scaling in DIS should be studied.

Local duality (averaging over finite range in x) should also be valid for elastic peak at x = 1 if analyzed in ξ

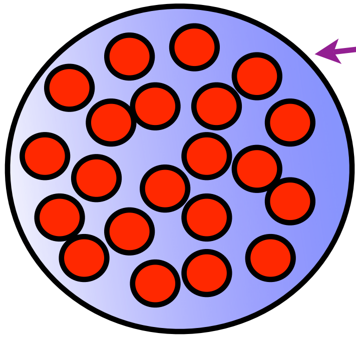


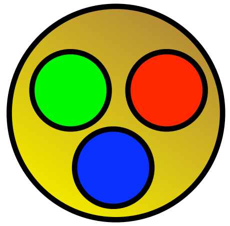
$$F_2^A(\xi) = \underbrace{\int_\xi^A dz F(z) F_2^n(\xi/z)}_{\text{averaging}}$$

Evidently the inelastic and quasielastic contributions cooperate to produce ξ scaling. Is this local duality?

Medium Modifications generated by high density configurations

Gold nucleus





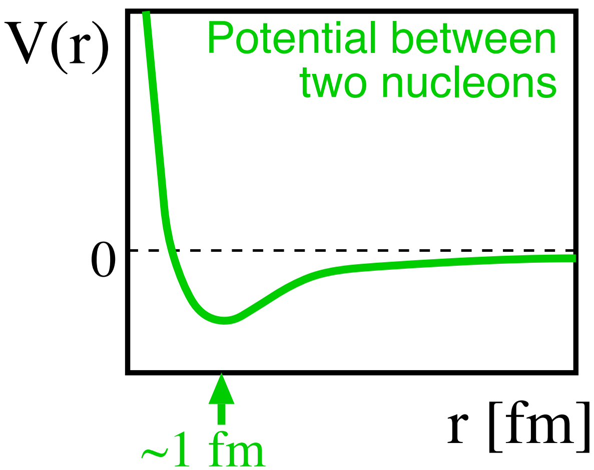
$$R = 1.2A^{1/3}$$

$$Volume = \frac{4}{3}\pi R^3 \simeq 1400 fm^3$$

A single nucleon, r = 1 fm, has a volume of 4.2 fm^3

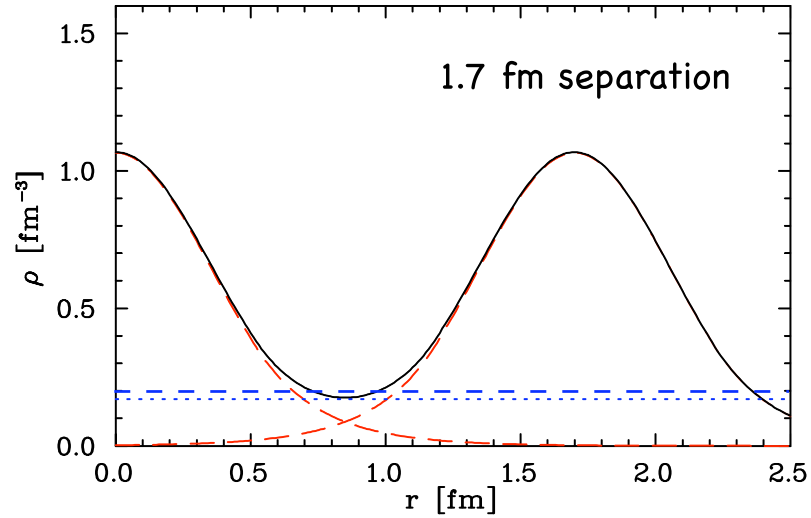
197 times 4.2 fm^3 ≈ 830 fm^3

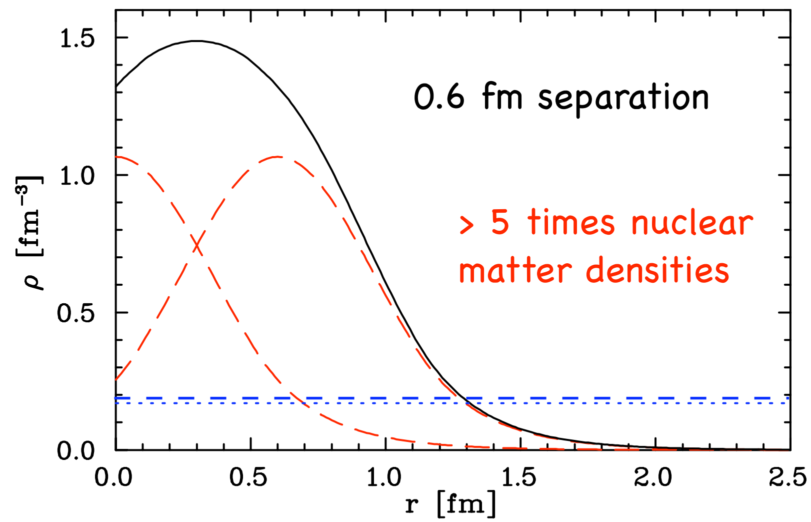
60% of the volume is occupied - very closely packed!



Nucleon separation is limited by the short range repulsive core

Even for a 1 fm separation, the central density is about 4x nuclear matter



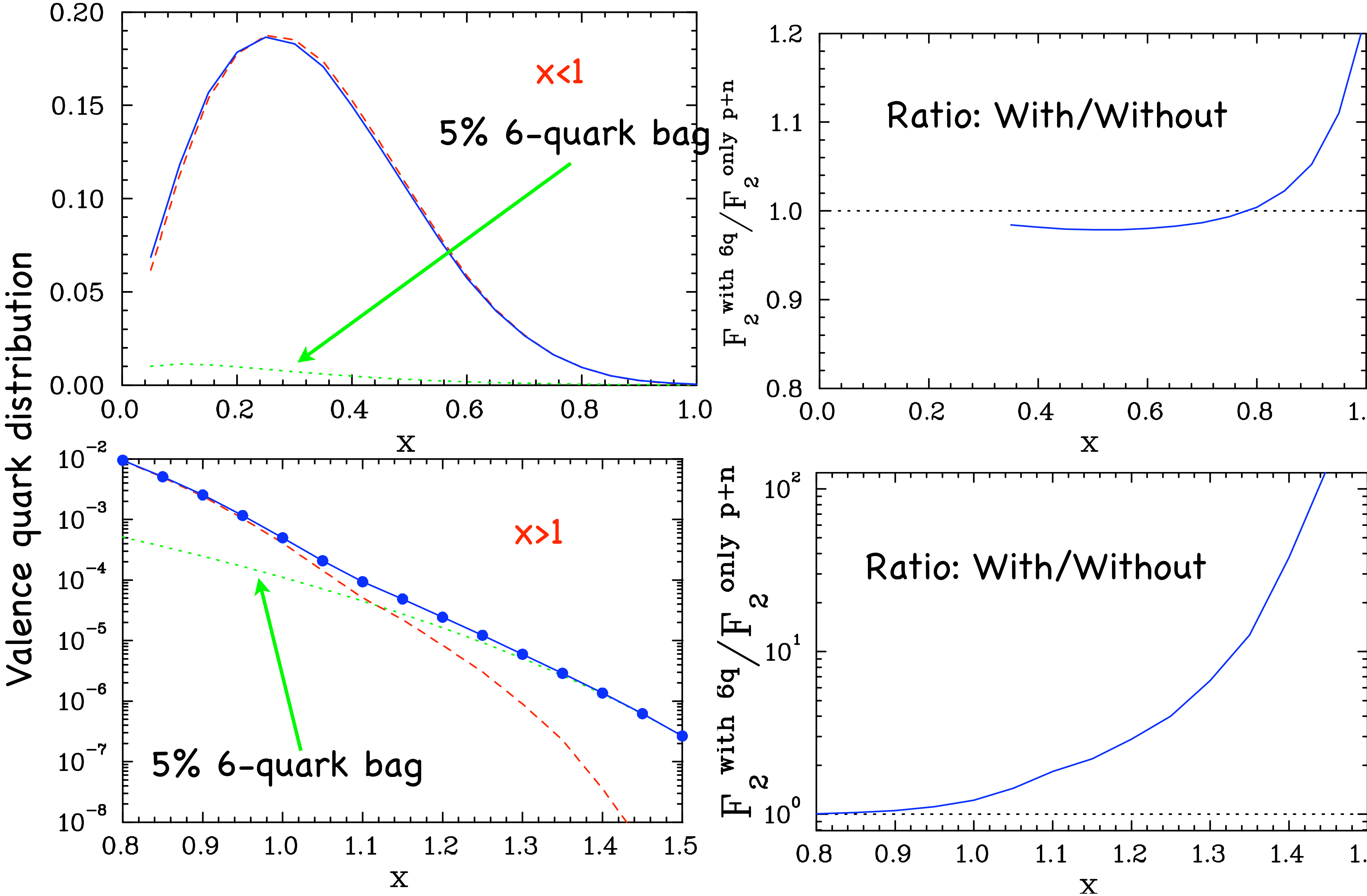


Comparable to neutron star densities!

High enough to modify nucleon structure?

To which nucleon does the quark belong?

Sensitivity to non-hadronic components



Mulders & Thomas

DIS at x > 1 or studying Superfast Quarks

- In the nucleus we can have 0<x<A
- In the Bjorken limit, x > 1 DIS tells us the virtual photon scatters incoherently from quarks
- Quarks can obtain momenta x>1 by abandoning confines of the nucleon
  - deconfinement, color conductivity, parton recombination multiquark configurations
  - correlations with a nucleon of high momentum (short range interaction)
- DIS at x > 1 is a filter that selects out those nuclear configurations in which the nucleon wave functions overlap. We are studying the dynamics of partons that have abandoned the confines of the nucleon.

$$\langle r_{NN} \rangle \approx 1.7 \text{ fm} \approx 2 \times r_n = 1.6 \text{ fm}$$

The probability that nucleons overlap is large and at x > 1 we are kinematically selecting those configurations.

Quark distributions at x > 1

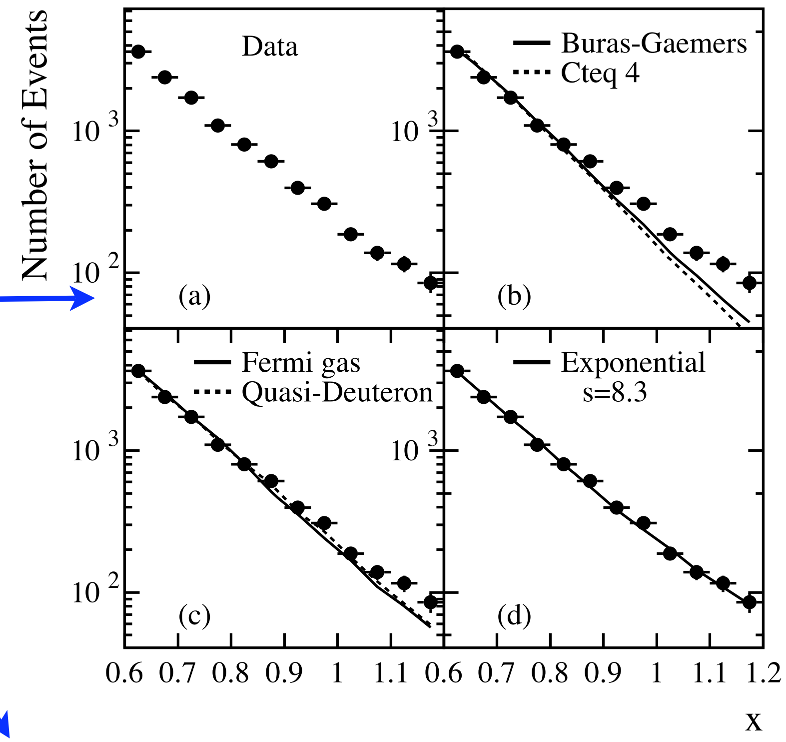
Two measurements (very high Q^2) exist so far:

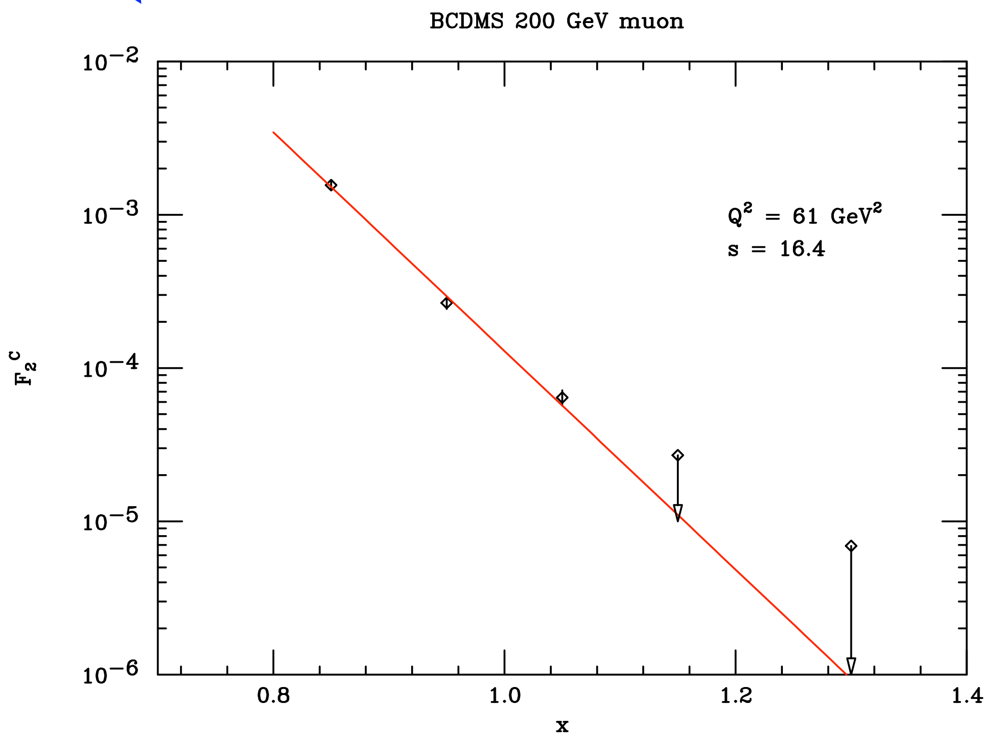
CCFR (ν-C): $F_2(x) \propto e^{-sx}$ s = 8

BCDMS (μ-Fe): $F_2(x) \propto e^{-sx}$ s = 16

Limited x range, poor resolution

Limited x range, low statistics



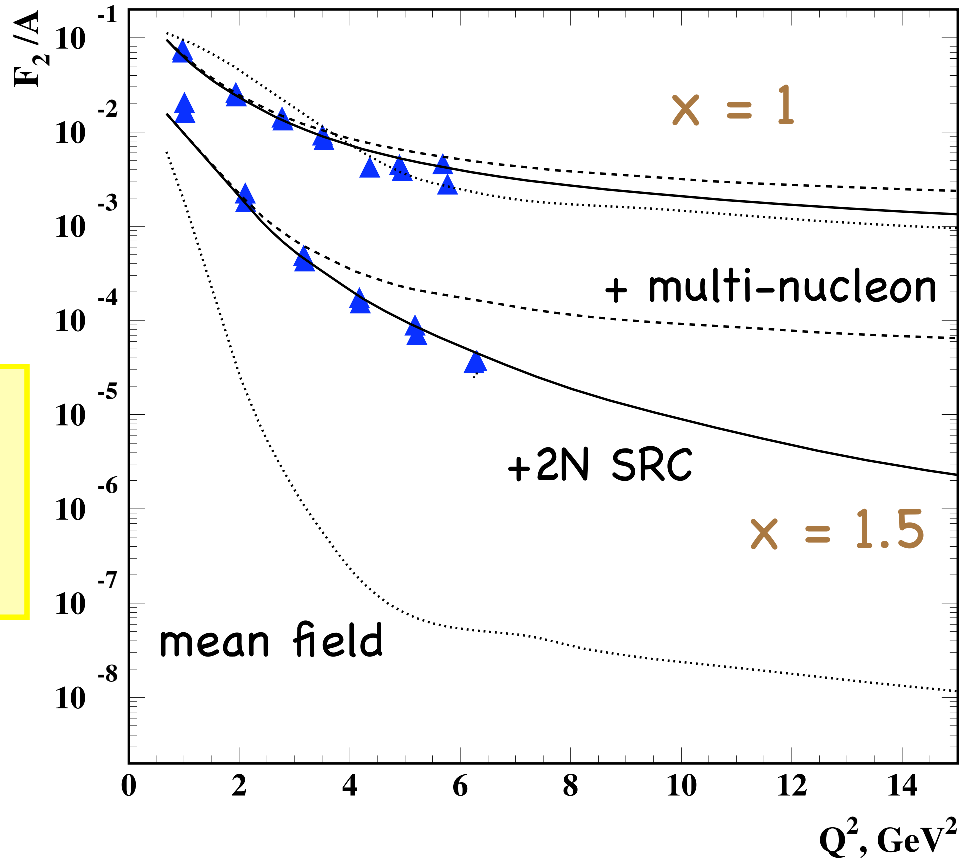


With 11 GeV beam, we should be in the scaling region up to x≈1.4

Sensitivity to SRC increase with Q^2 and x

We want to be able to isolate and probe two-nucleon and multi-nucleon SRCs

Dotted = mean field approx.
Solid = +2N SRCs.
Dashed = +multi-nucleon.

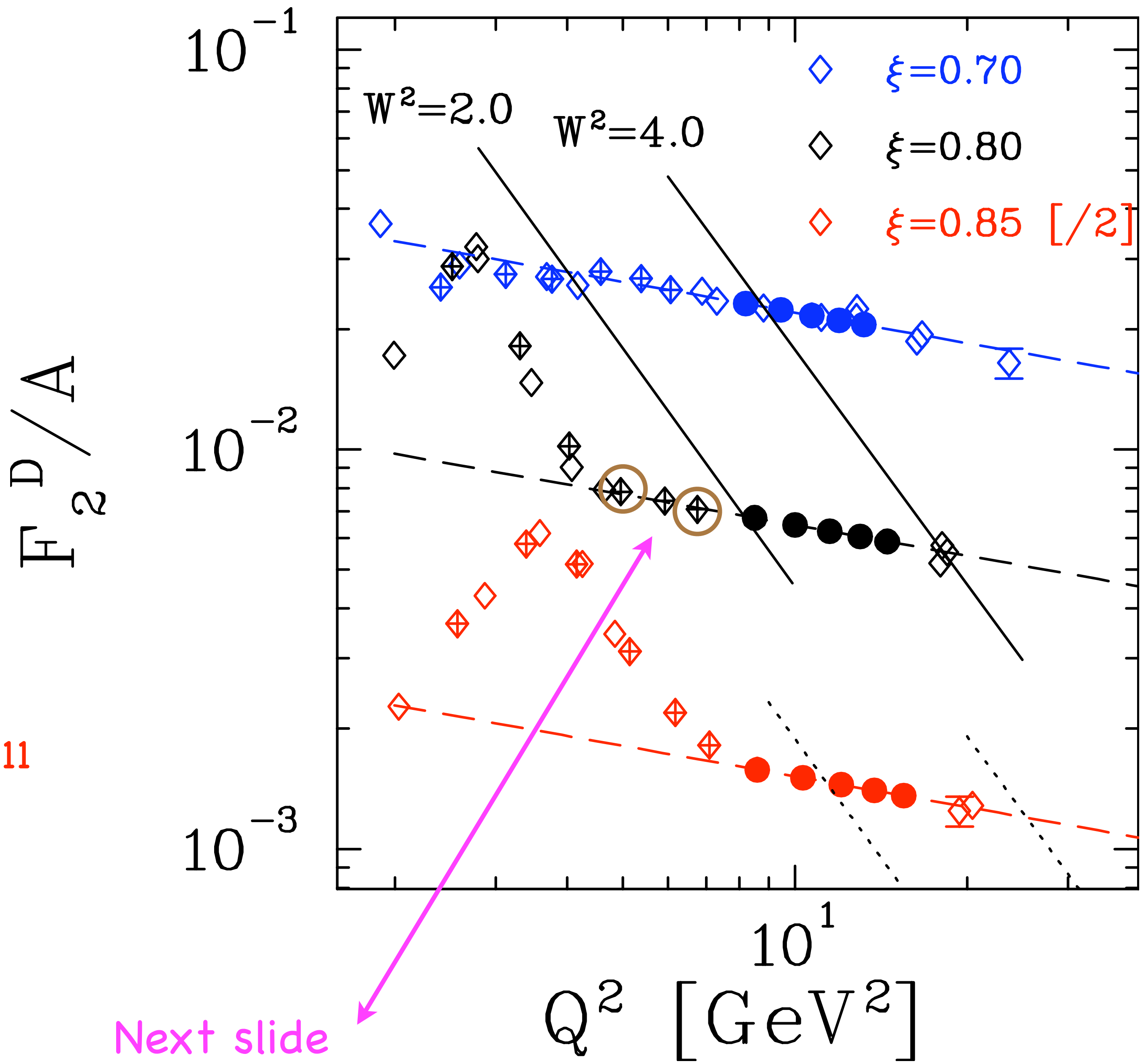


11 GeV can reach Q^2= 20(13) GeV^2 at x = 1.3(1.5)

- very sensitive, especially at higher x values

Approach to Scaling - Deuteron

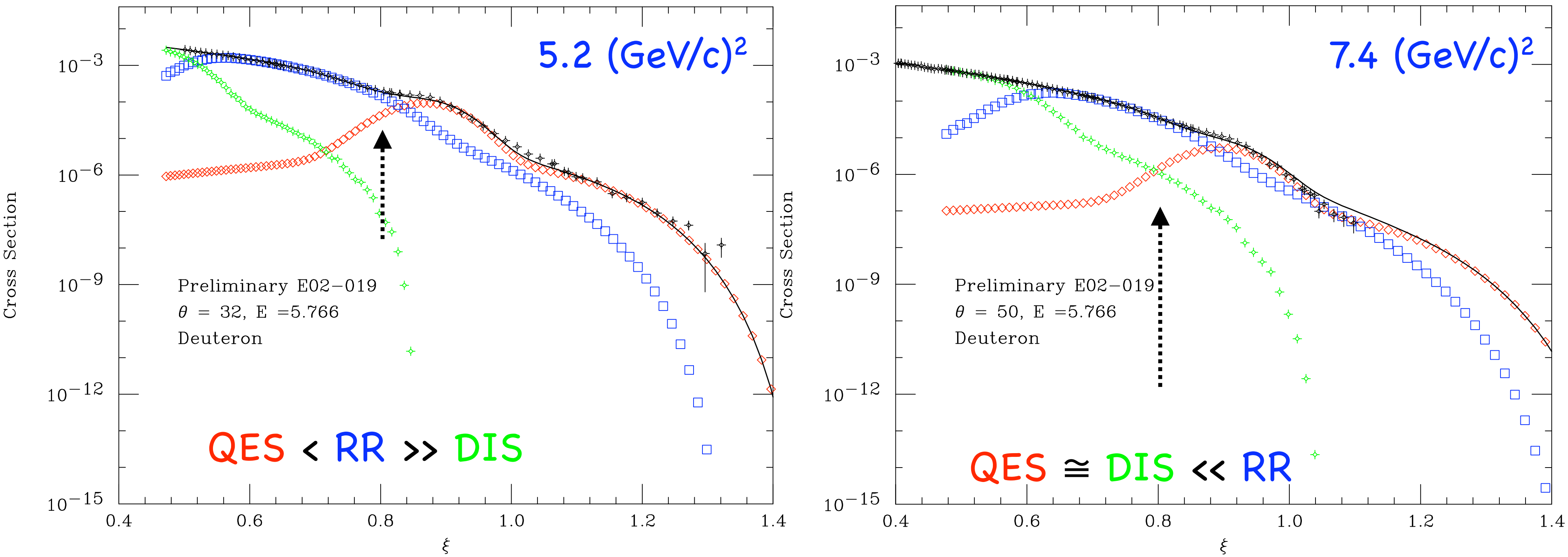
Dashed lines are arbitrary normalization (adjusted to go through the high Q^2 data) with a constant value of $d\ln(F_2)/d\ln(Q^2)$



filled dots - experiment with 11 GeV

Next slide

Approach to Scaling (Deuteron)



Convolution model

QES

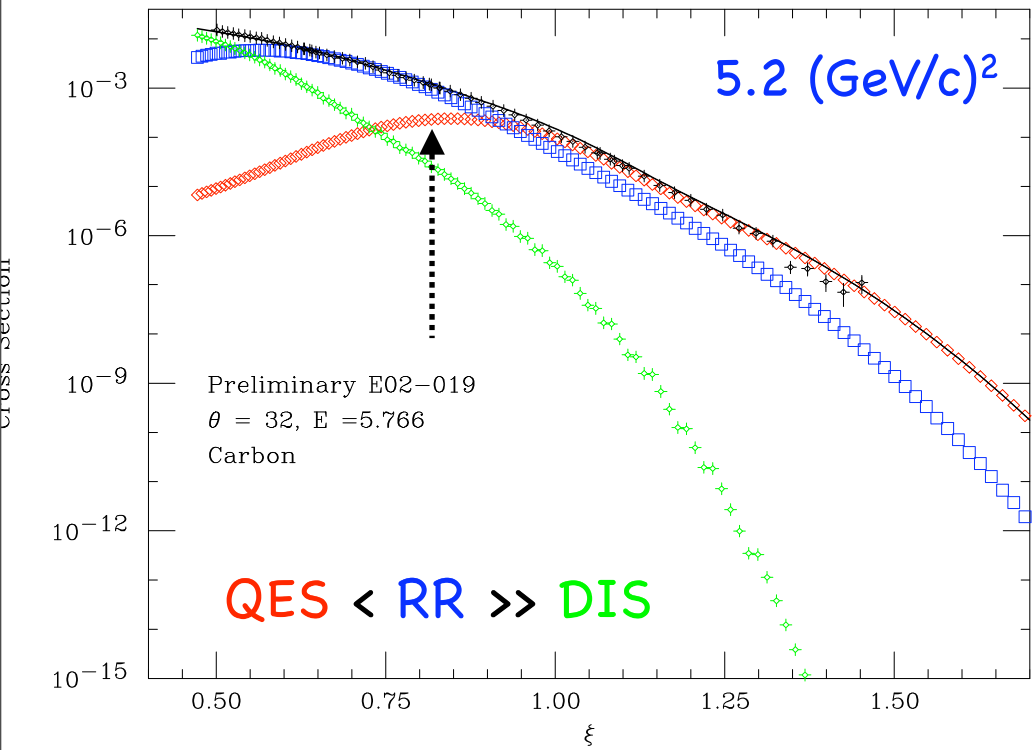
RR ($W^2 < 4$)

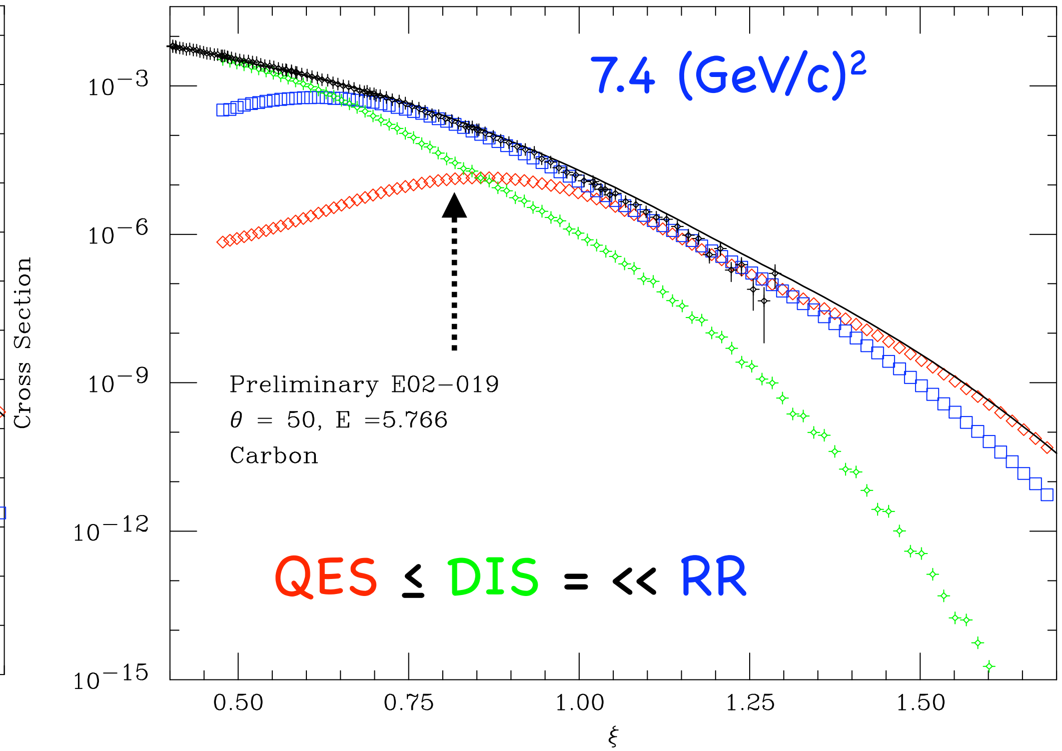
DIS ($W^2 > 4$)

Scaling appears to work well even in regions where the DIS is not the dominate process

We can expect that any scaling violations will melt away as we go to higher Q^2

Approach to Scaling (Carbon)





Convolution model

QES

RR ($W^2 < 4$)

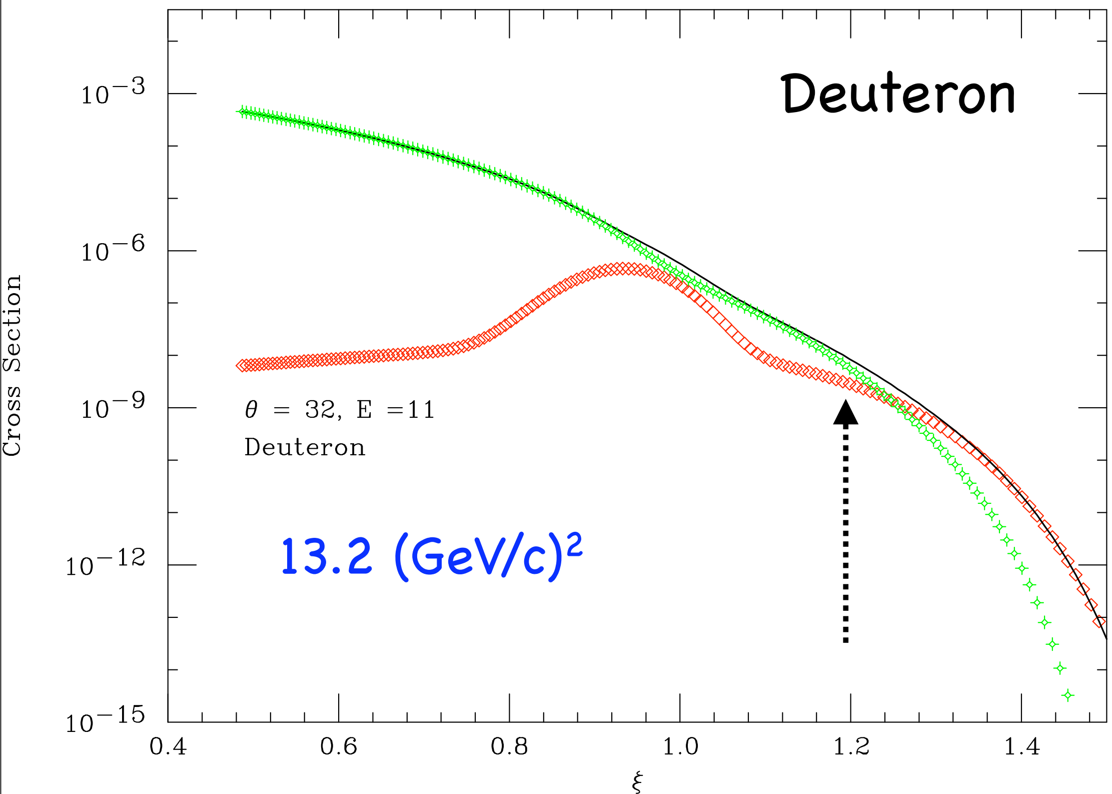
DIS ($W^2 > 4$)

Scaling appears to work well even in regions where the DIS is not the dominate process

We can expect that any scaling violations will melt away as we go to higher Q^2

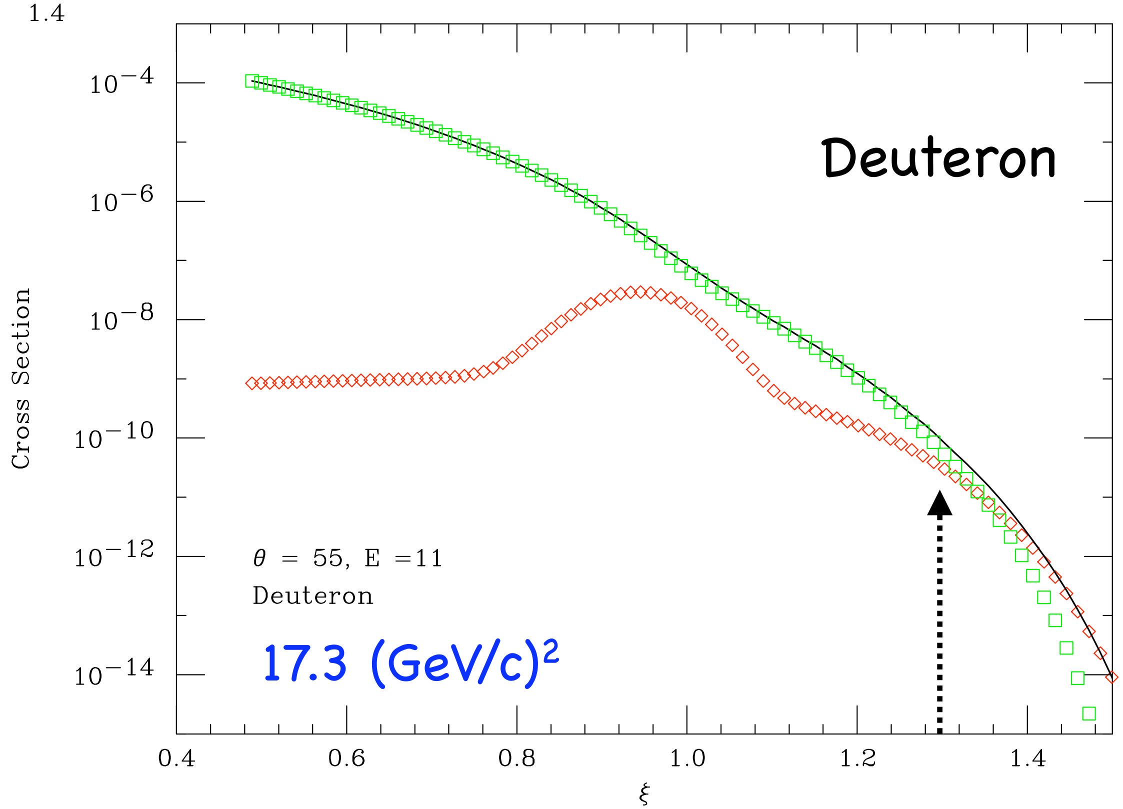
Quark distributions at x > 1

Predictions for 11 GeV



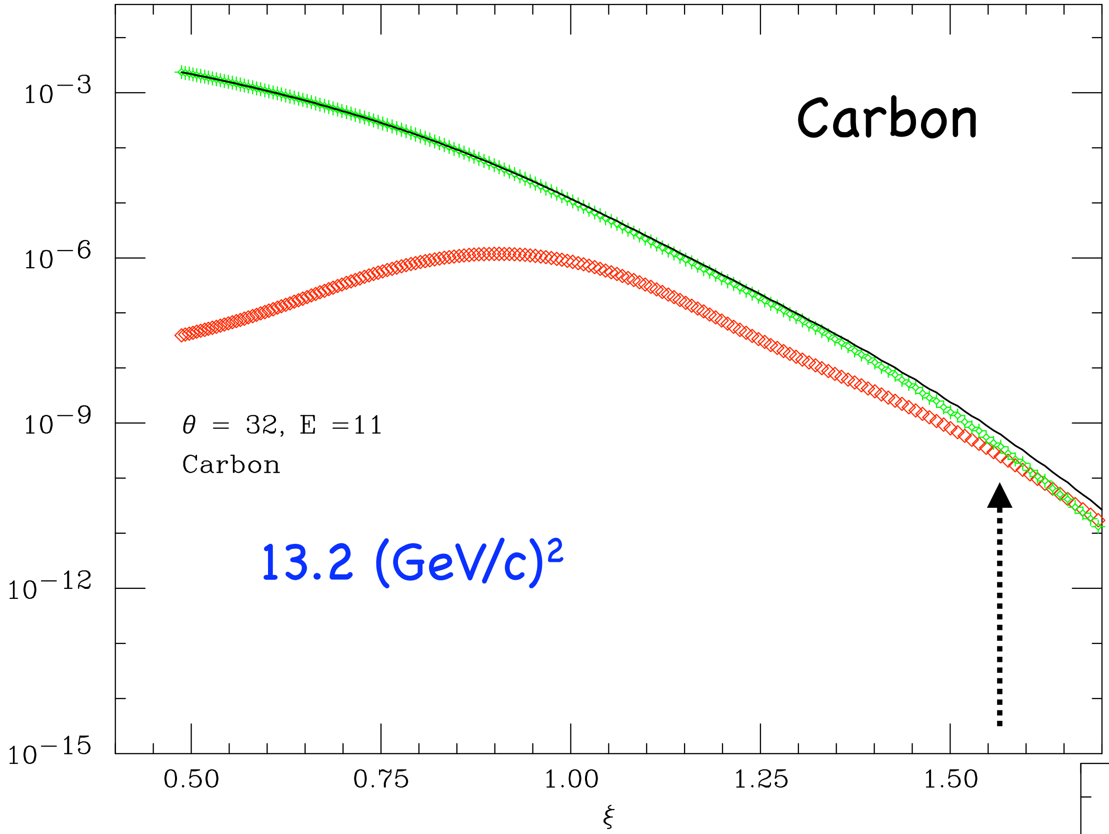
Convolution model
QES
DIS + RR

Deuteron is worst case as narrow QE peak makes for larger scaling violations



Quark distributions at x > 1

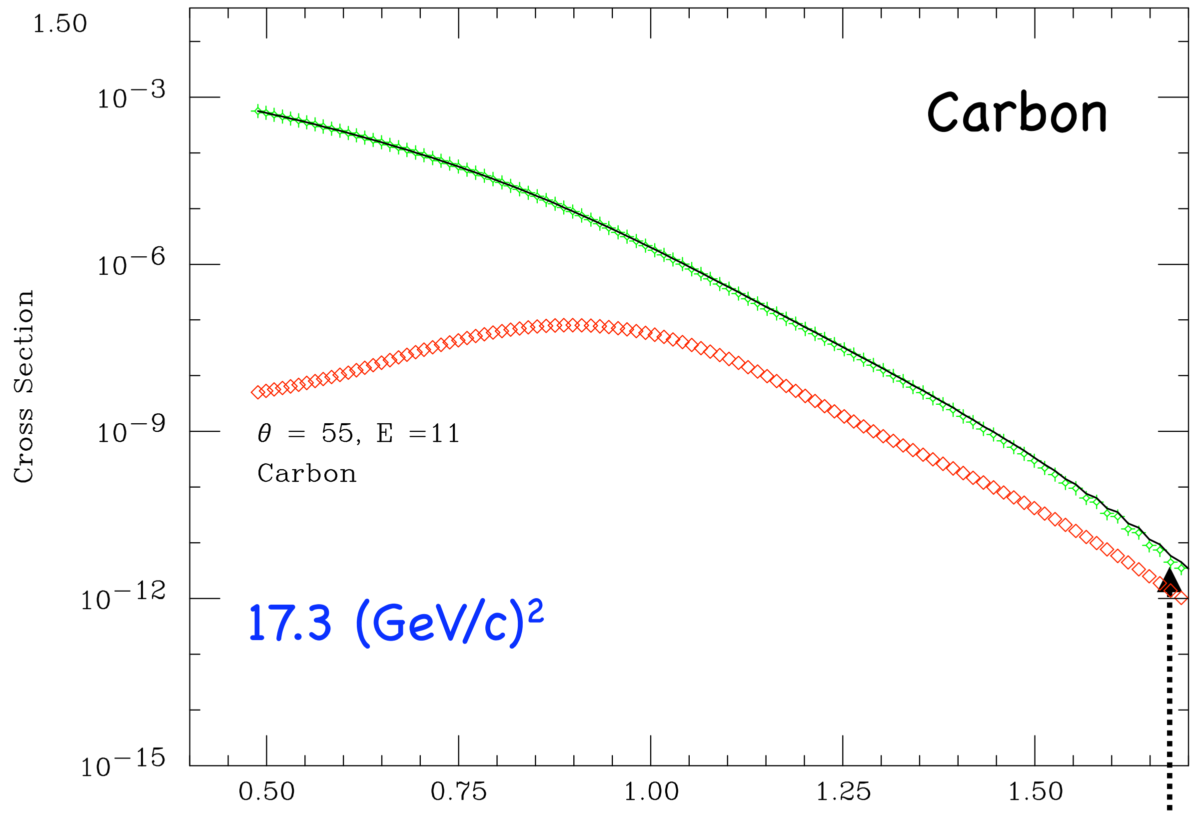
Predictions for 11 GeV



Convolution model

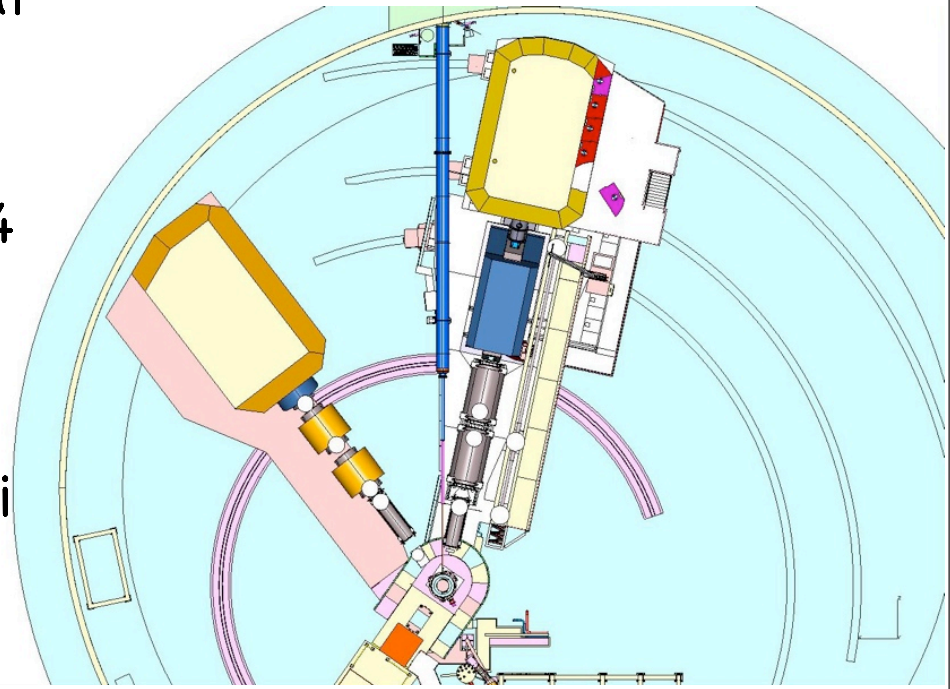
QES

DIS + RR

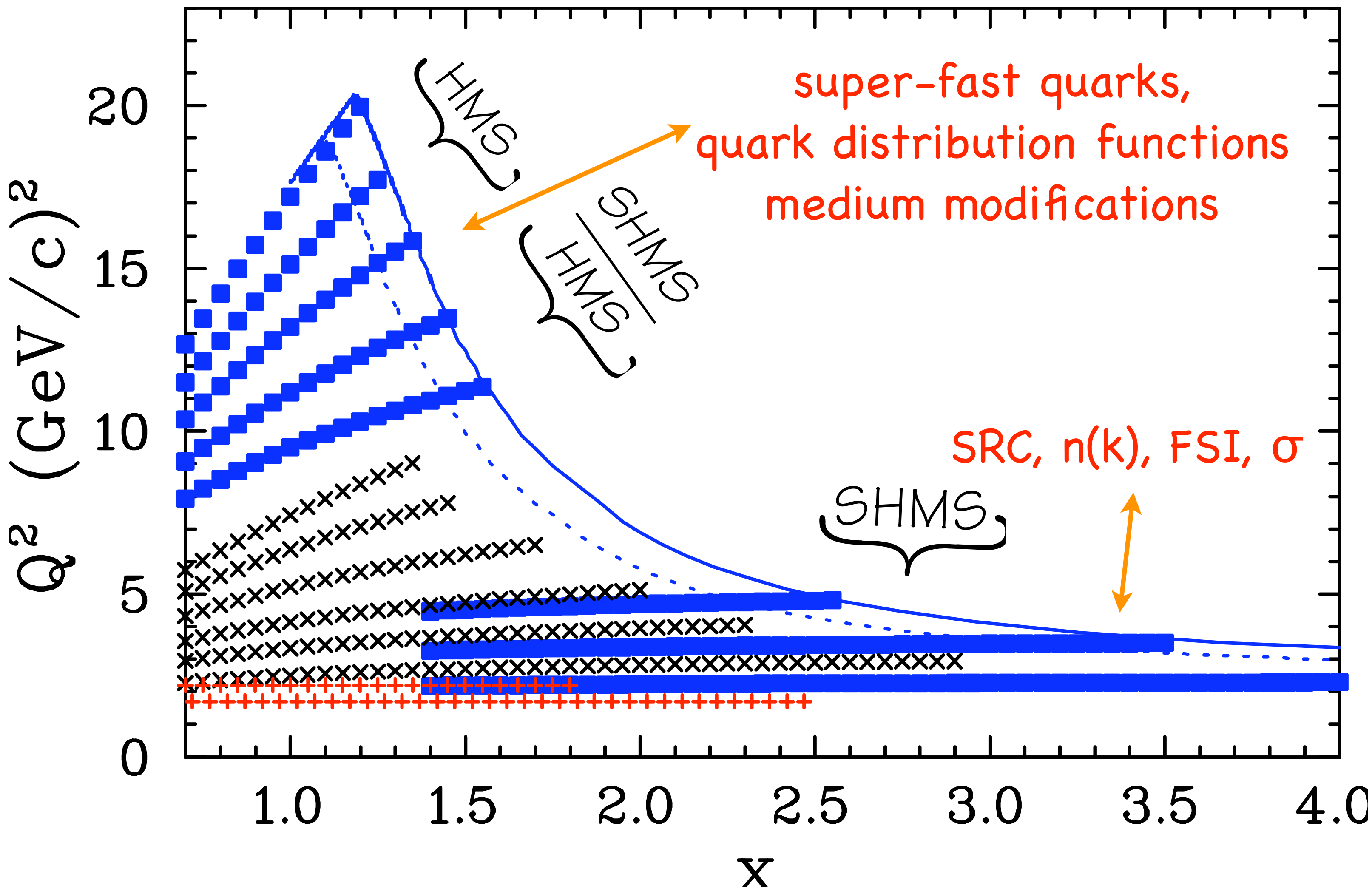


Inclusive DIS at x > 1 at 12 GeV

- New proposal approved at JLAB PAC30
- Target ratios (and absolute cross sections) in quasielastic regime: map out 2N, 3N, 4N correlations
- Measure nuclear structure functions (parton distributions) up to $x = 1.3 - 1.4$
  - Extremely sensitive to non-hadronic configurations
- Targets include several few-body nuclei allowing precise test of theory.
- Extend measurements to large enough Q^2 to fully suppress the quasielastic contribution
- Extract structure functions at $x > 1$
- $Q^2 \approx 20$ at $x=1$, $Q^2 \approx 12$ at $x = 1.5$



Kinematic range to be explored



Black - 6 GeV, red - CLAS, blue - 11 GeV

Summary

- High Q^2 scattering at $x>1$ holds great promise and is not nearly fully exploited.
- Window on wide variety of interesting physics.
- Provides access to SRC and high momentum components through y-scaling, ratios of heavy to light nuclei, φ'-scaling
- Testing ground for EMC models of medium modification, quark clusters, and other non-hadronic components
- DIS is does not dominate over QES at 6 GeV but should be at 11 GeV and at $Q^2 > 10 - 15$ $(\mathrm{GeV}/c)^2$.
- Experiments are relatively straightforward. JLAB at 12 GeV will significantly expand the coverage in x-Q^2

Review paper (Benhar, Day and Sick) nucl-ex/0603029, RMP