Inclusive scattering at x>1

A review of the physics and the prospects at 12 GeV

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University of Virginia

Topical Workshop on Short-Range Correlations in Nuclei
Jefferson Lab, October 20-21, 2006

DD & Kim Egiyan
EEP03 Grenoble, 2003

Proposal to 50-GeV meeting at SLAC June 3-4, 1991

Measuring of nuclear structure functions for $x_{Bj}>1$.

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Introduction

The goal of proposed experiment is measuring of the fundamental characteristic of nuclei - their structure function. The experiment is aimed basically to investigate the range $0.8<X_{Bj}<2$, where there are almost no experimental data. It is intended to obtain data for the H, D, He, C, Al, Cu and Pb nuclei at $Q^2 > 10\ (GeV/c)^2$, i.e. in the deep inelastic scattering region.

The nuclear structure function at least at $X_{Bj} > 1.2$ is determined by the nonnucleon degrees of freedom (multiquark bags [1], short range few-nucleon correlations [2],...). A lot of data [3] on cumulative particle production indicate the significant role of the nonnucleon degrees of freedom in the high energy nuclear reactions. The combined analysis of data on nuclear structure functions and cross sections of cumulative particle production will allow to investigate the hadronization process in the nuclear matter.

The detailed measuring of A-dependence of the structure functions will allow to estimate the contributions of clusters with different masses in different nuclei. The comparison with the data at lower Q^2 [4] will allow to investigate the transition from quasielastic to deep inelastic regime at $X_{Bj} > 1$.

Small cross section of (e,e') reaction at the discussed X_{Bj} and Q^2 region will require the high luminosity, which can be achieved only using the electron beam of high intensity. The demands on Q^2 and ν lead to the beam energy not less than 20 GeV, hence in the nearest future such an experiment can be performed only at SLAC.

Outline

✳ Introduction

✳ Inclusive Scattering

✳ SRC in QES and DIS

✳ Dense Nuclear Matter

✳ Approach to scaling

✳ An experiment at 11 GeV

✳ Conclusion

Introduction

Inclusive electron scattering can be labeled as old-fashioned but it is clear that inclusive electron scattering from nuclei provides a rich, yet complicated mixture of physics that has yet to be fully exploited.

Compelling Physics to be Studied

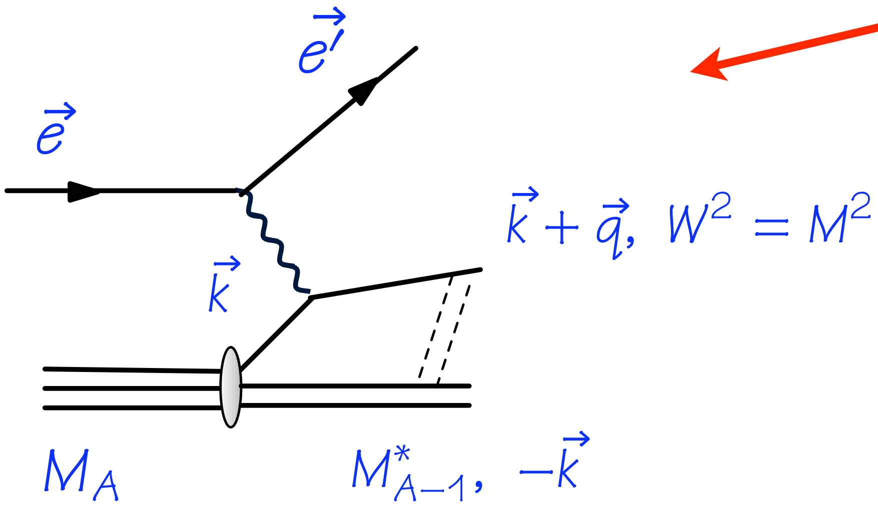
- Momentum distributions and the spectral function P(k,E).
- Short Range Correlations and Multi-Nucleon Correlations
- Scaling (x, y, φ', ξ)
- Medium Modifications -- tests of EMC; 6-quark admixtures
- Parton Recombination
- Duality
- Structure Function Q^2 dependence and Higher Twists

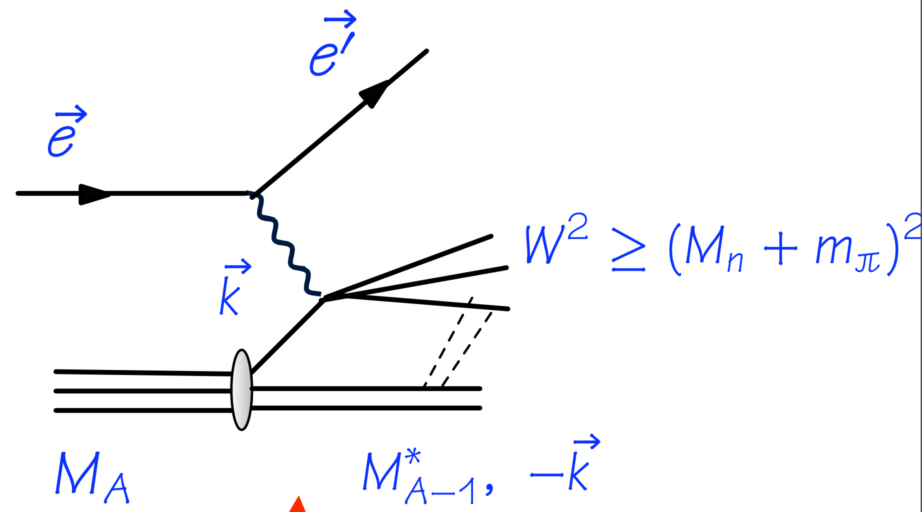
The inclusive nature of these studies make disentangling all the different pieces a challenge but experiments over a range of Q^2 and with different A will help.

Inclusive Quasielastic and Deep Inelastic Scattering at High Momentum Transfers

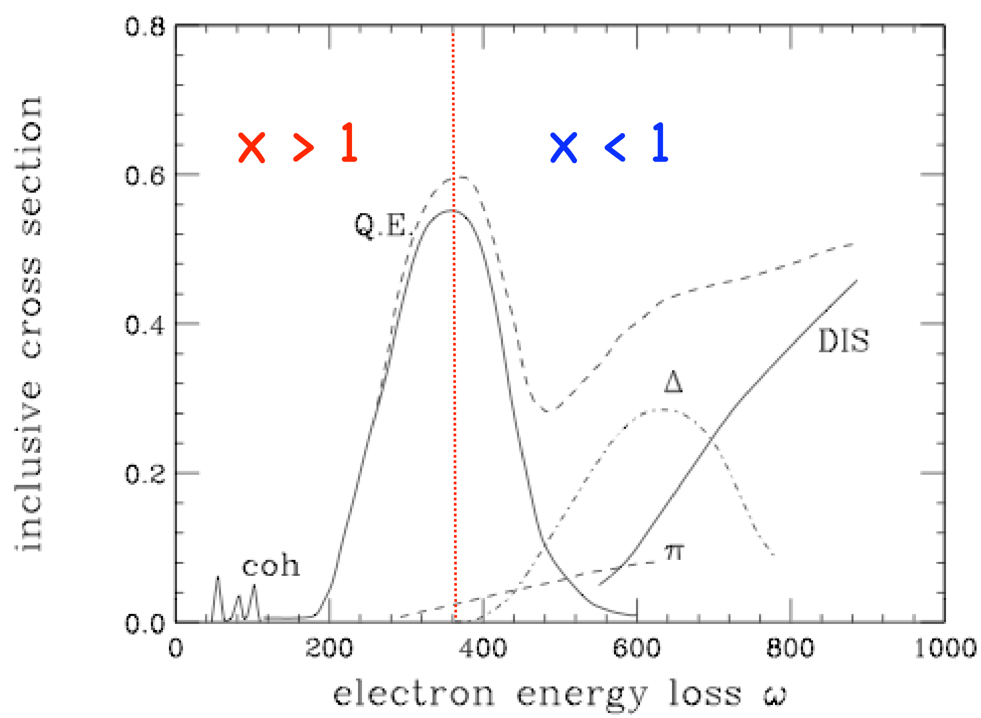
Two distinct processes

Quasielastic from the nucleons in the nucleus

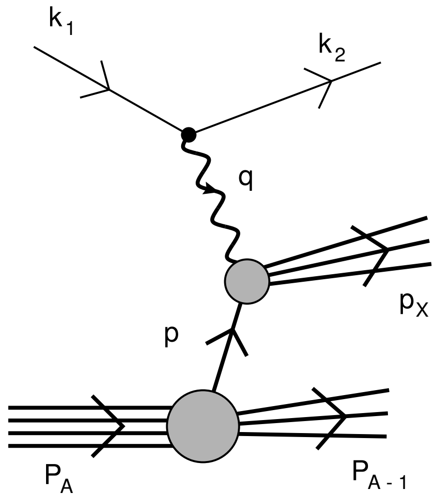




Inelastic, Deep Inelastic from the quark constituents of the nucleon.



Inclusive final state means no separation of two dominant processes



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

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

The two processes share the same initial state

QES in PWIA

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

DIS

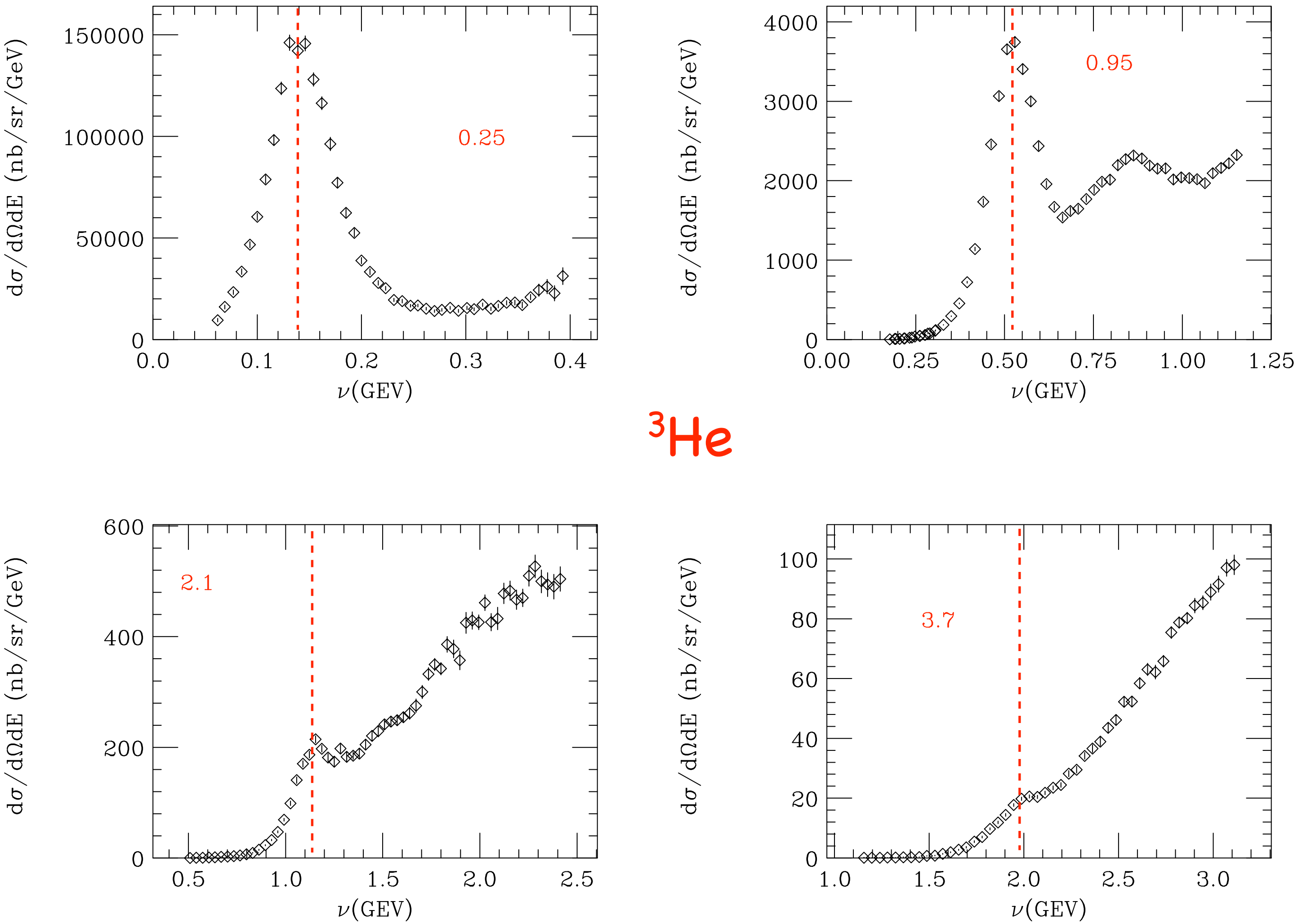
$$\frac{d^2\sigma}{d\Omega d\nu} \propto \int d\vec{k} \int dE\, W_{1,2}^{(p,n)} \underbrace{S_i(k,E)}_{\text{Spectral function}}$$

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

However they have very different Q^2 dependencies

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

Exploit this Q^2 dependence

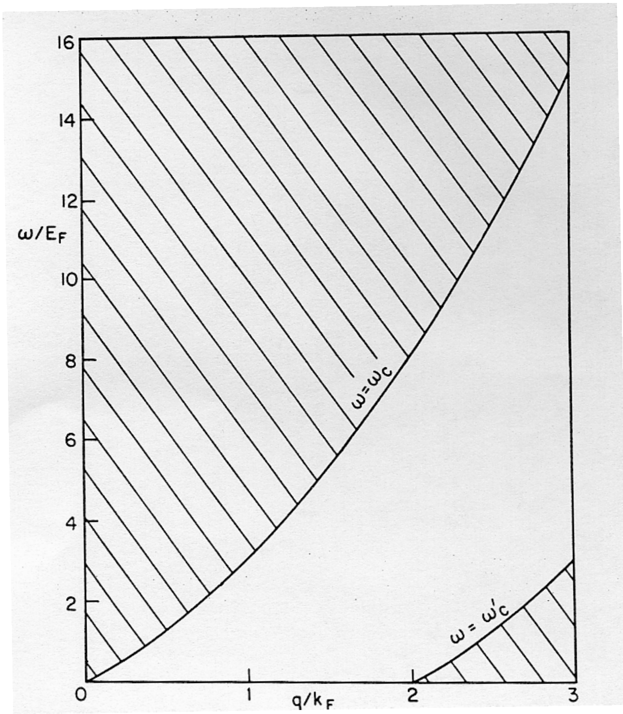


The quasielastic peak (QE) is broadened by the Fermi-motion of the struck nucleon.

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.

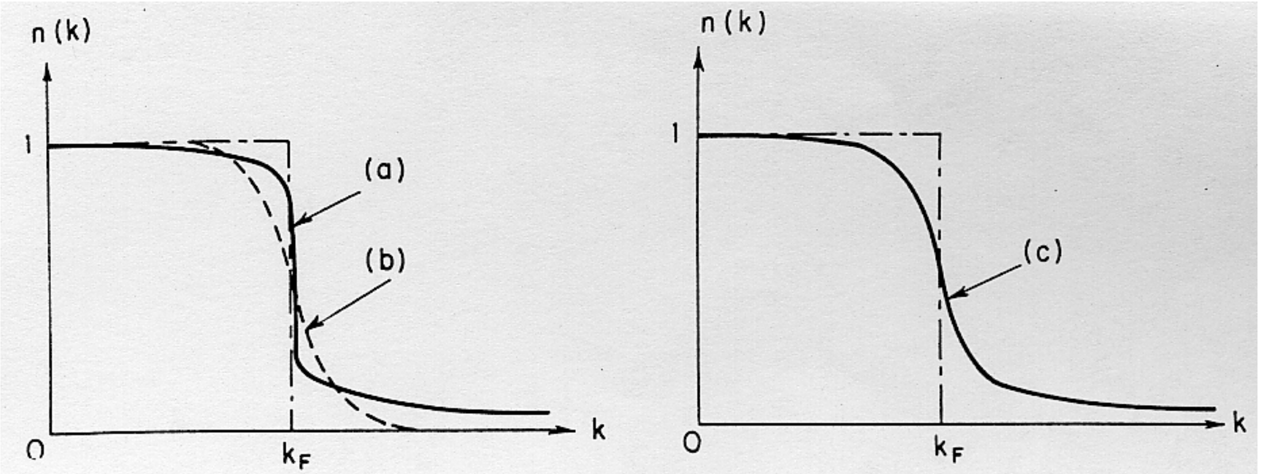
Correlations and Inclusive Scattering



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: $k < k_F$

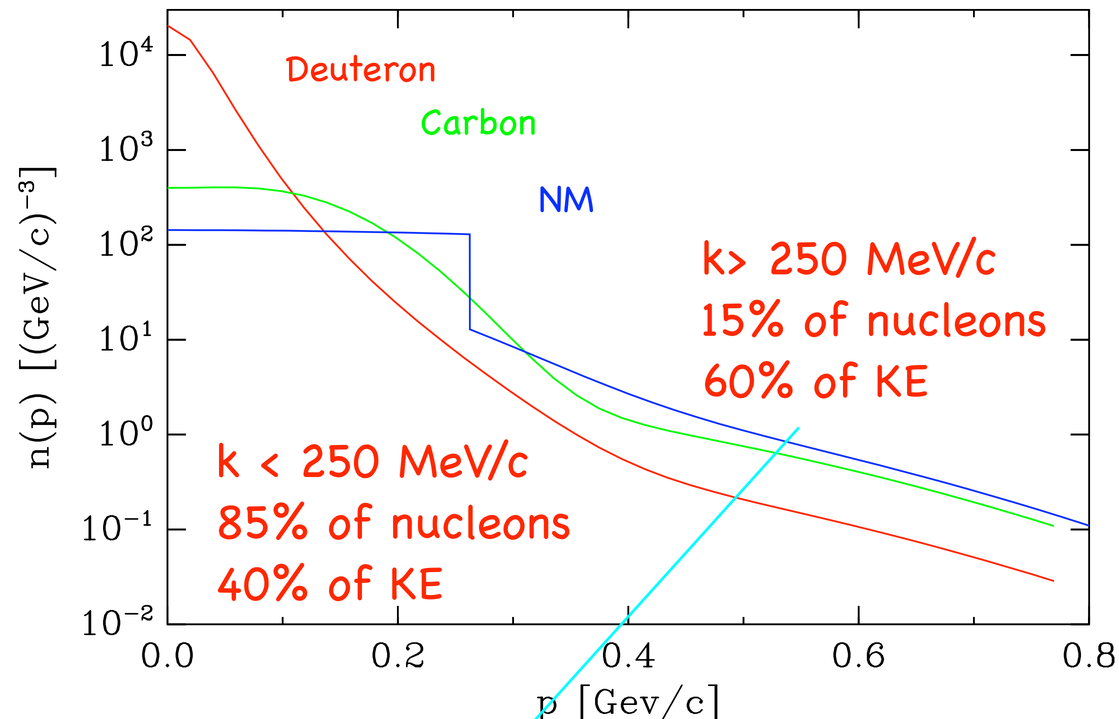
Well understood

High momentum tails: $k > k_F$

Calculable for few-body nuclei, nuclear matter.

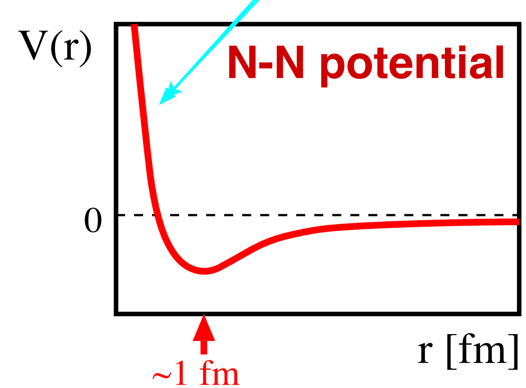
Dominated by two-nucleon short range correlations

Isolate short range interactions (and SRC's) by probing at high p_m



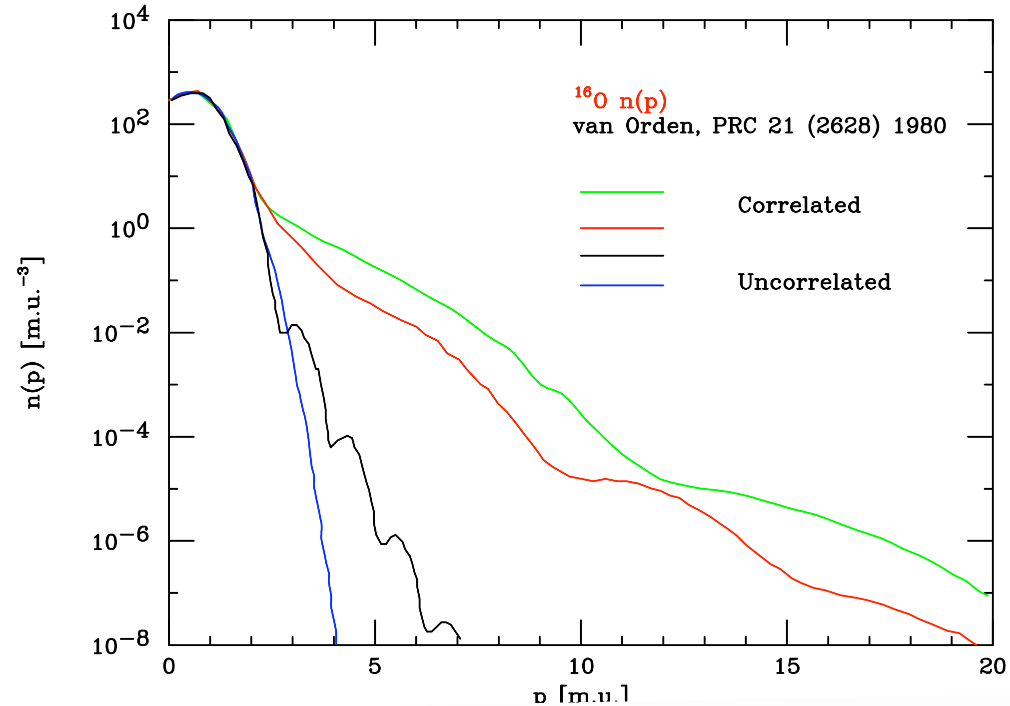
Poorly understood part of nuclear structure

Sign. fraction have $k > k_F$

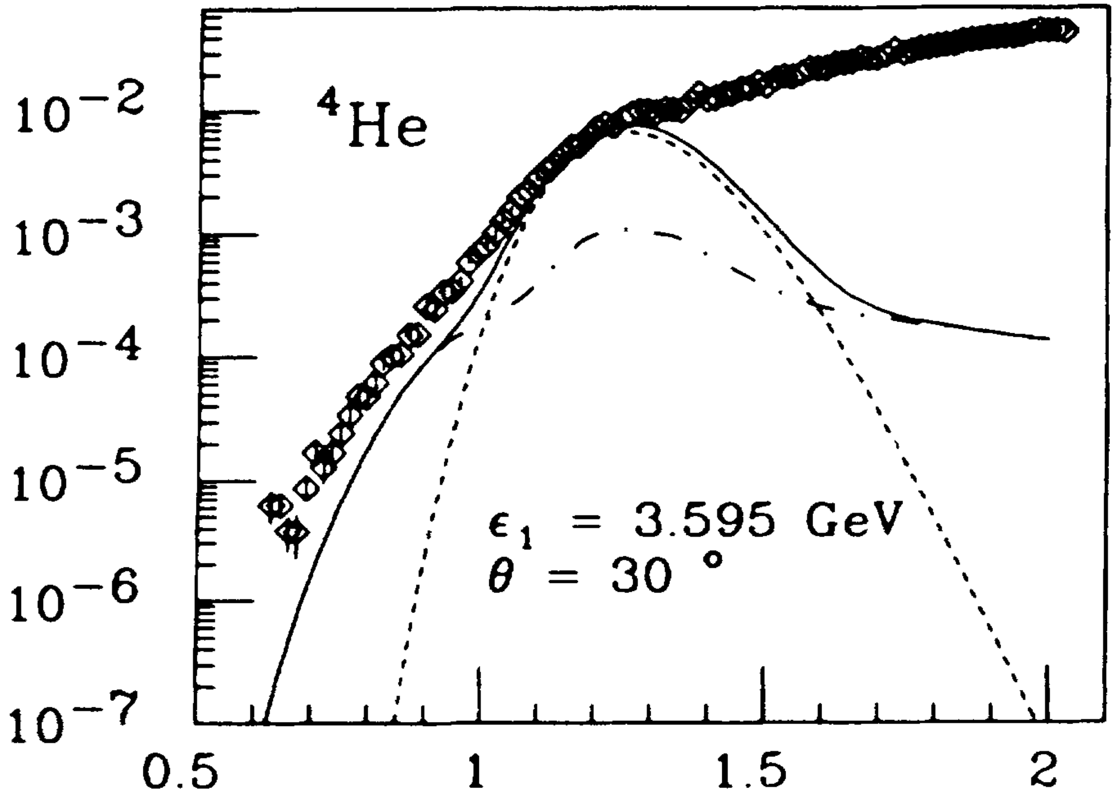


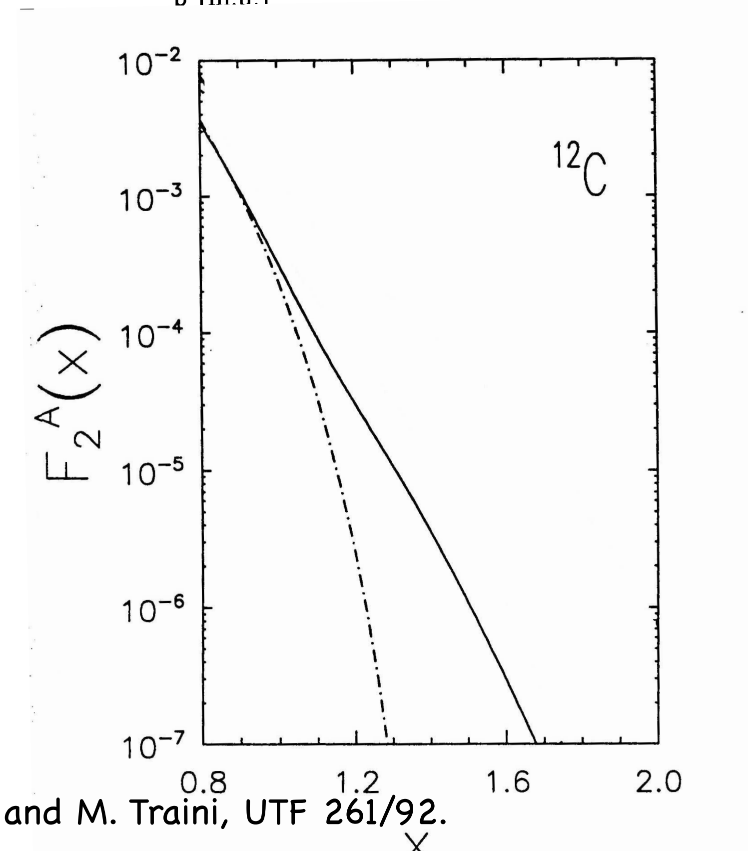
Uncertainty in SR interaction leads to uncertainty at k>>, even for simplest systems

Correlations contribute to both in QES and DIS



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

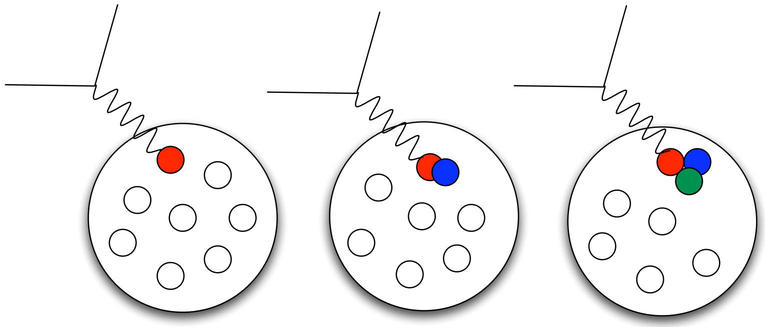




L. Conci and M. Traini, UTF 261/92.

Short Range Correlations

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.

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

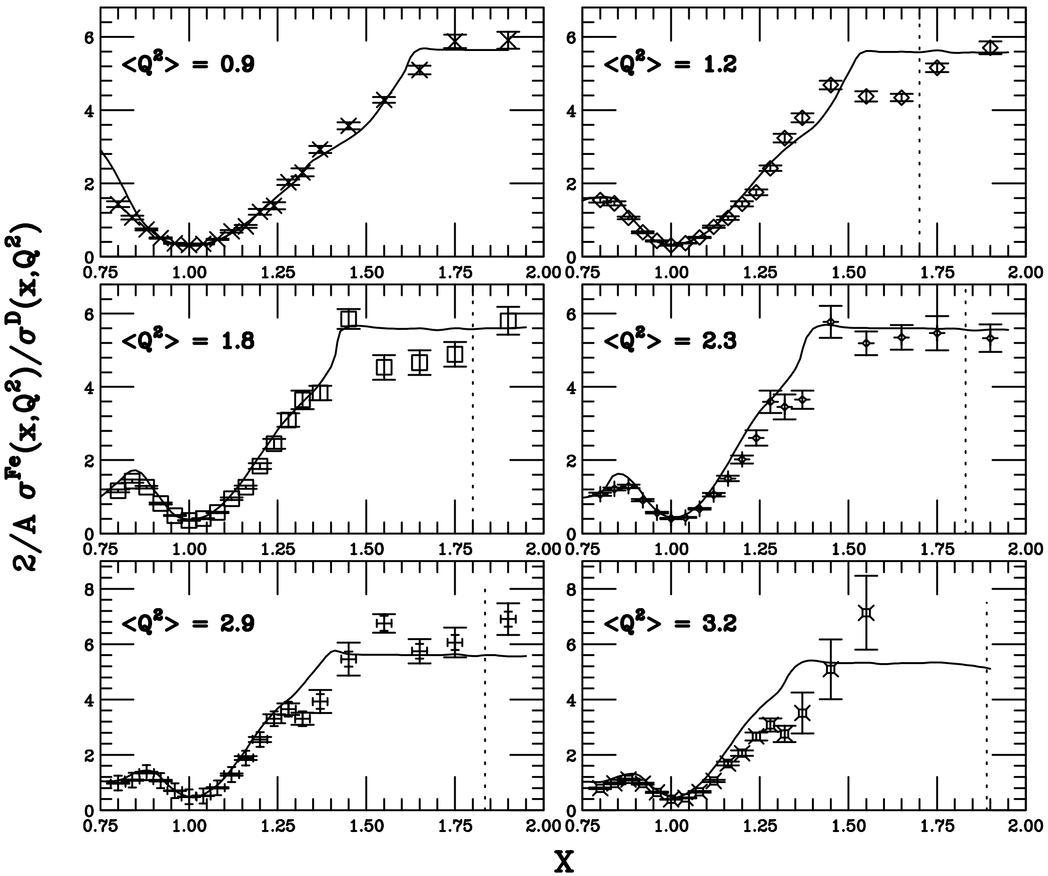
$$\Rightarrow \quad \frac{2}{A}\frac{\sigma_A(x,Q^2)}{\sigma_D(x,Q^2)} = a_2(A)\Big|_{1<x\leq 2}$$

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

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

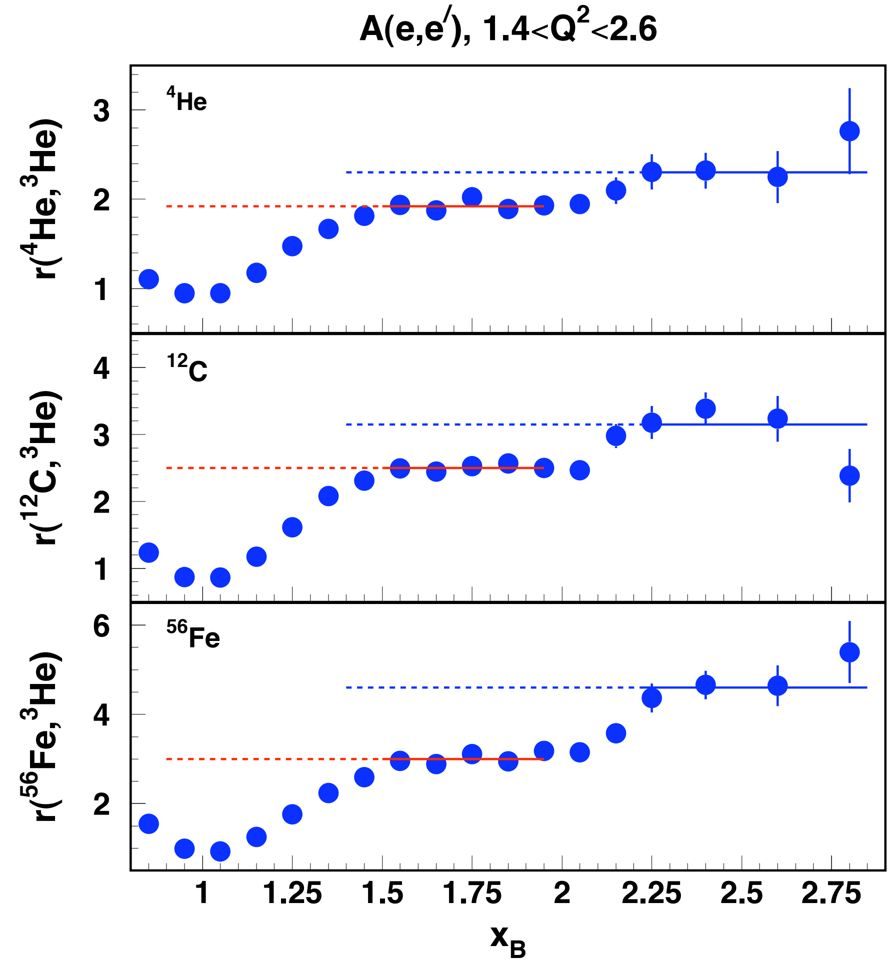
$a_j(A)$ is proportional to probability of finding a j-nucleon correlation

Short Range Correlations



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

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



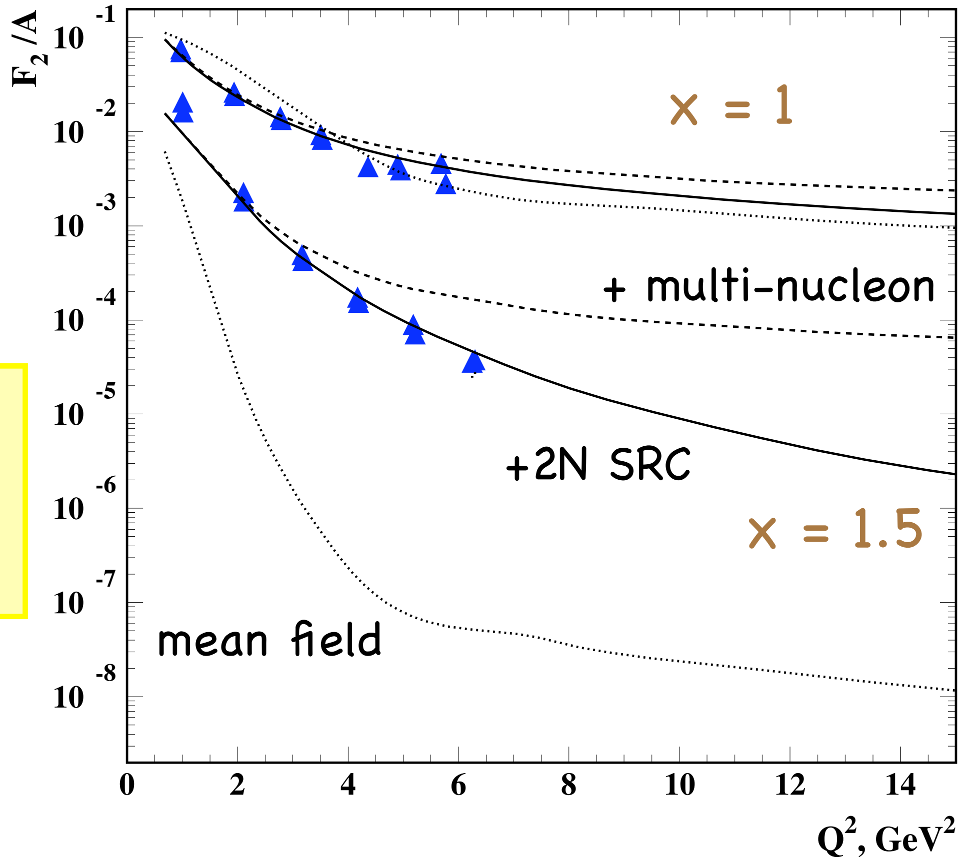
$a_j(A)$ is proportional to probability of finding a j-nucleon correlation

CLAS data

Egiyan et al., PRL 96, 082501, 2006

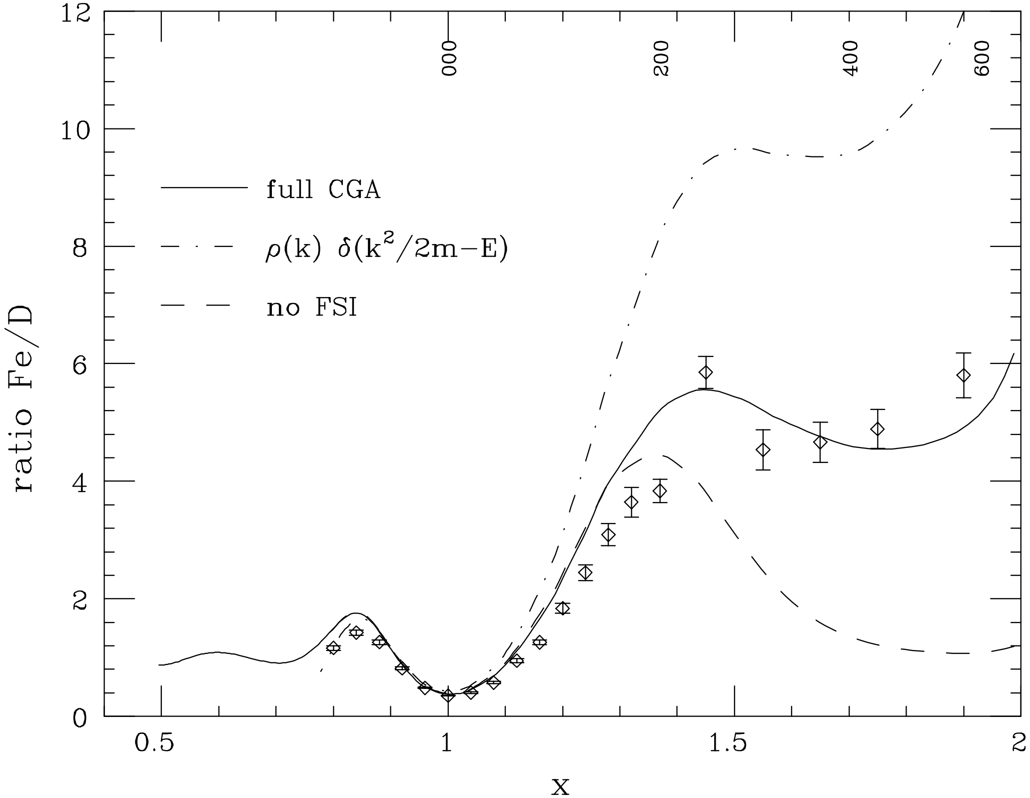
Sensitivity to SRC

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



Arguments about role of FSI

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

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

Scaling

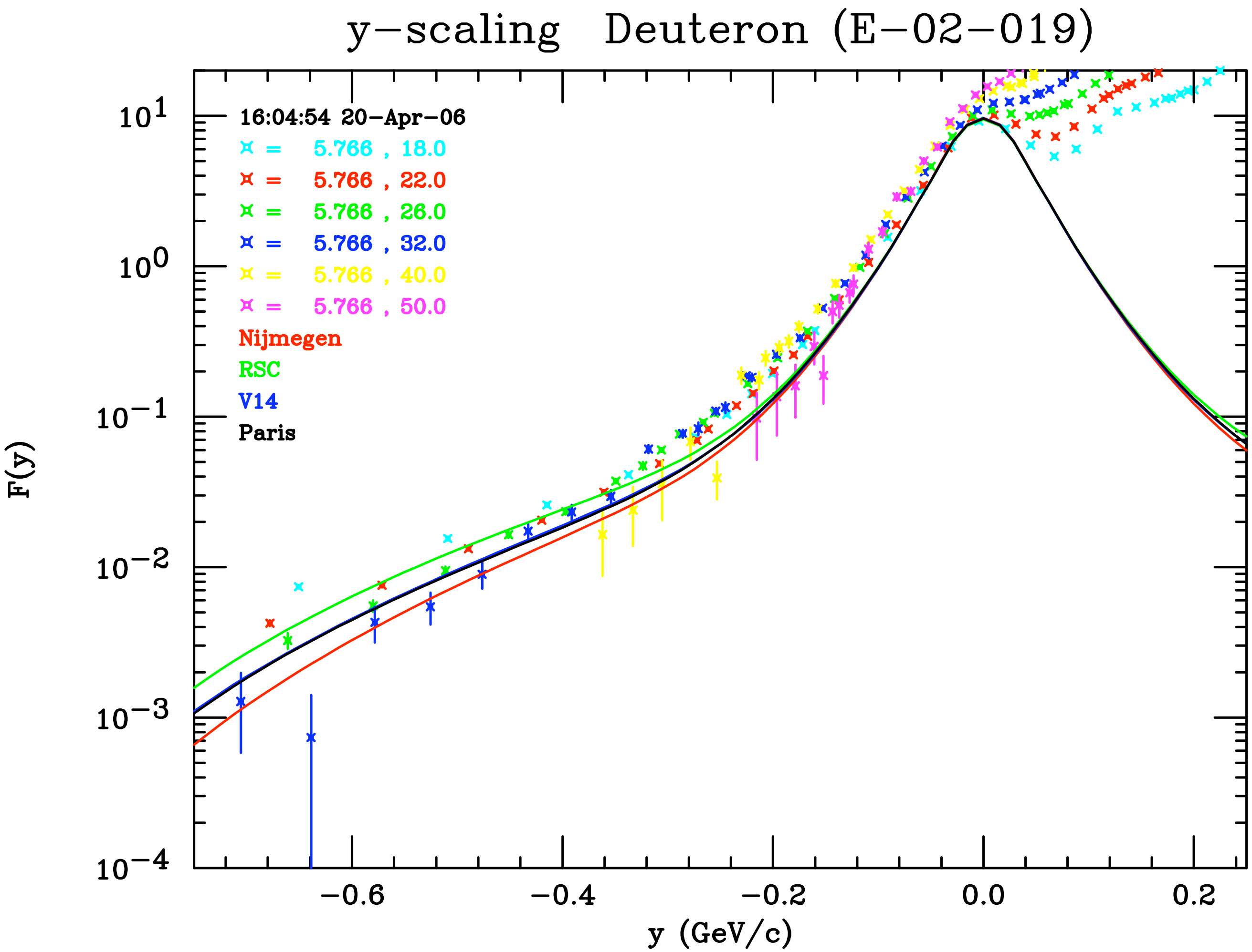
- Scaling refers to the dependence of a cross section, in certain kinematic regions, on a single variable. If the data scales in the single variable then it validates the assumptions about the underlying physics and scale-breaking provides information about conditions that go beyond the assumptions.

- Scaling of DIS at SLAC in 1960's in terms of the Bjorken x-variable provided evidence for the existence of quarks.

- 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 a quasi-free nucleons.

- 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.

Deuteron



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

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

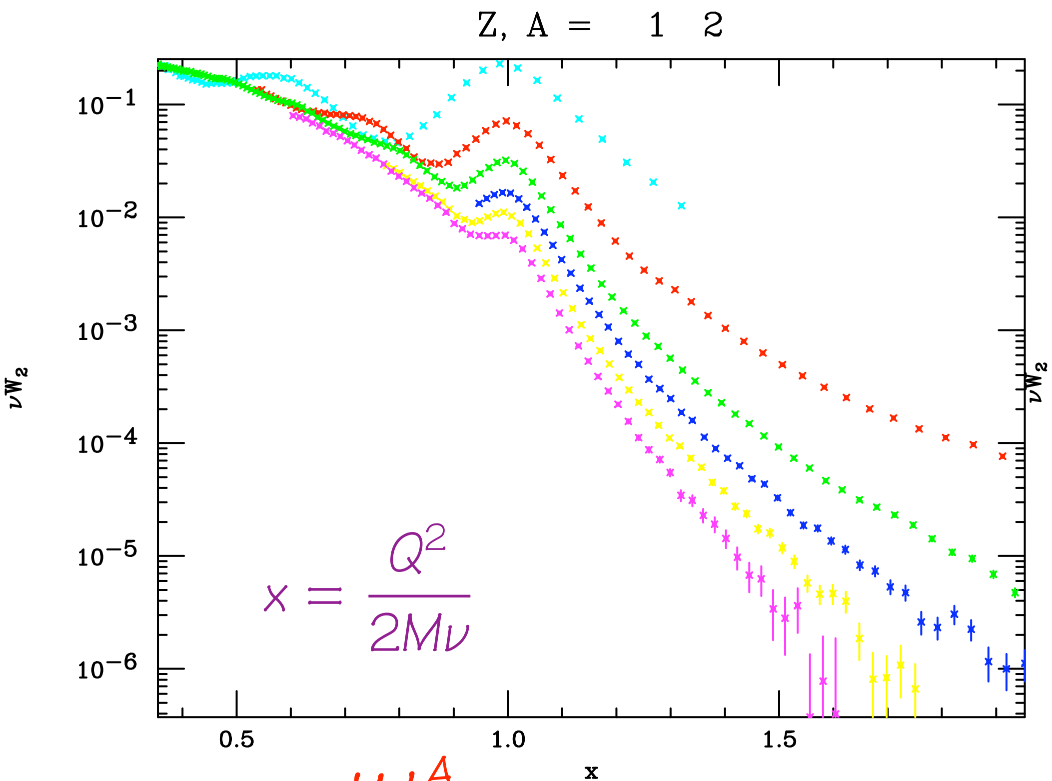
Assumption: scattering takes place from a quasi-free proton or neutron in the nucleus.

y is the momentum of the struck nucleon parallel to the momentum transfer:

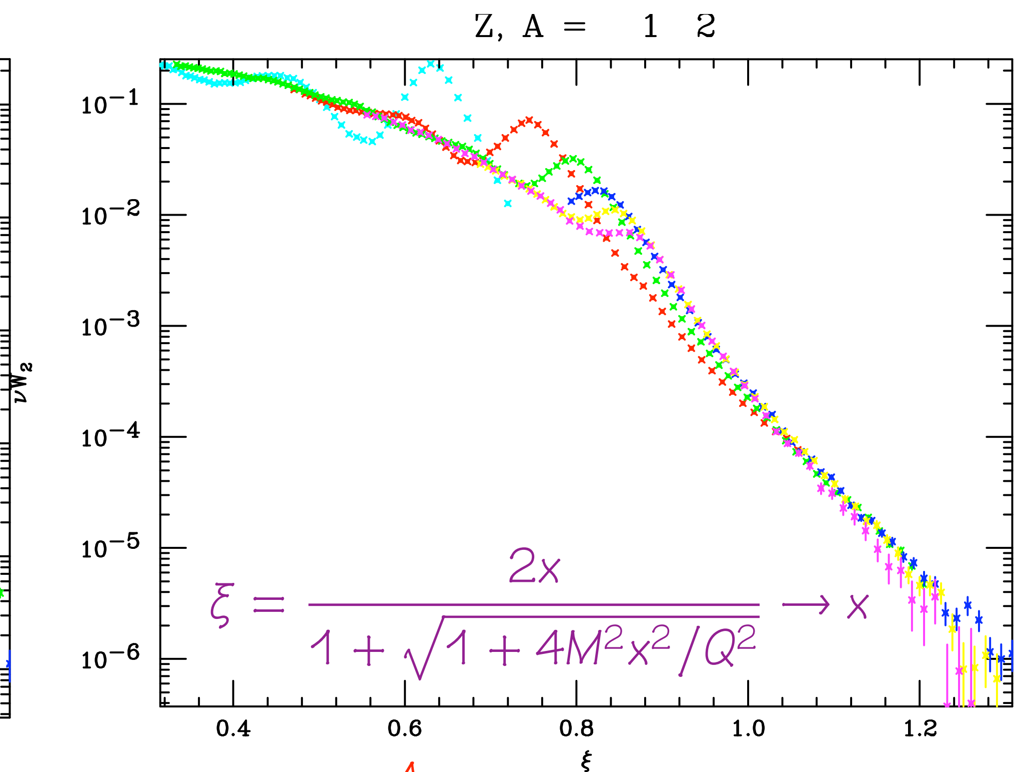
$y \approx -q/2 + m\nu/q$

x and ξ scaling

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

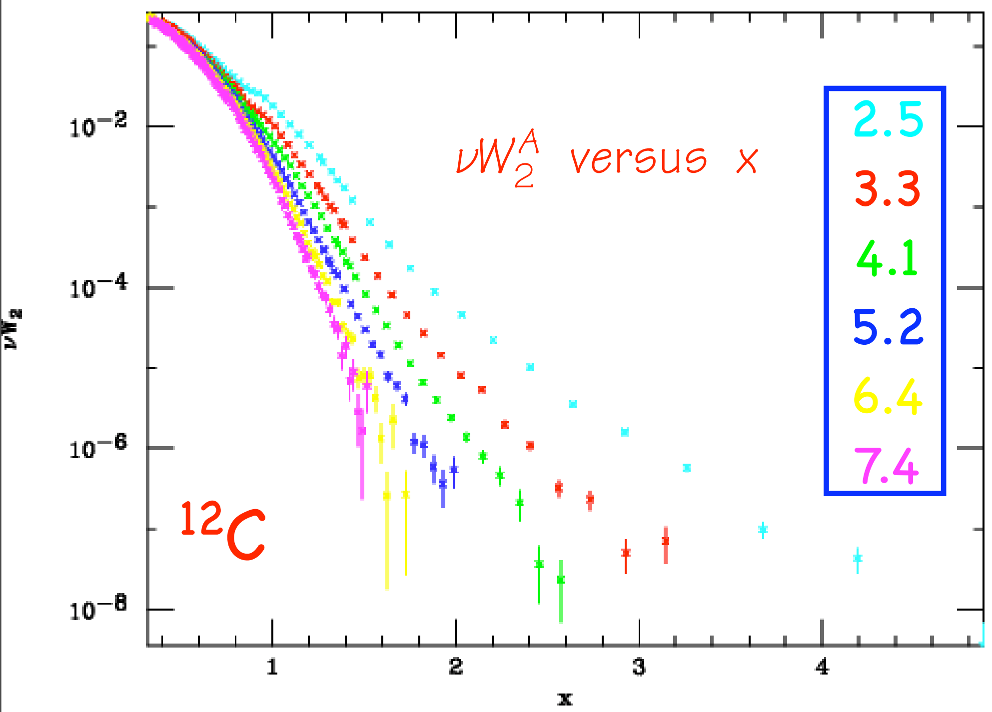


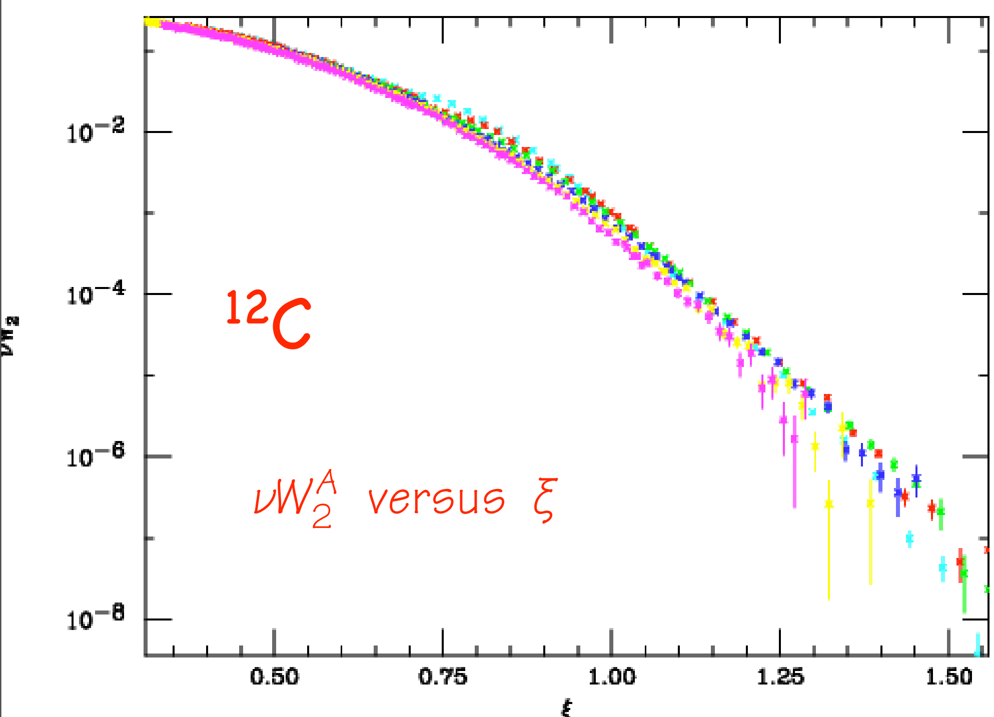
νW_2^A versus x



νW_2^A versus ξ

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





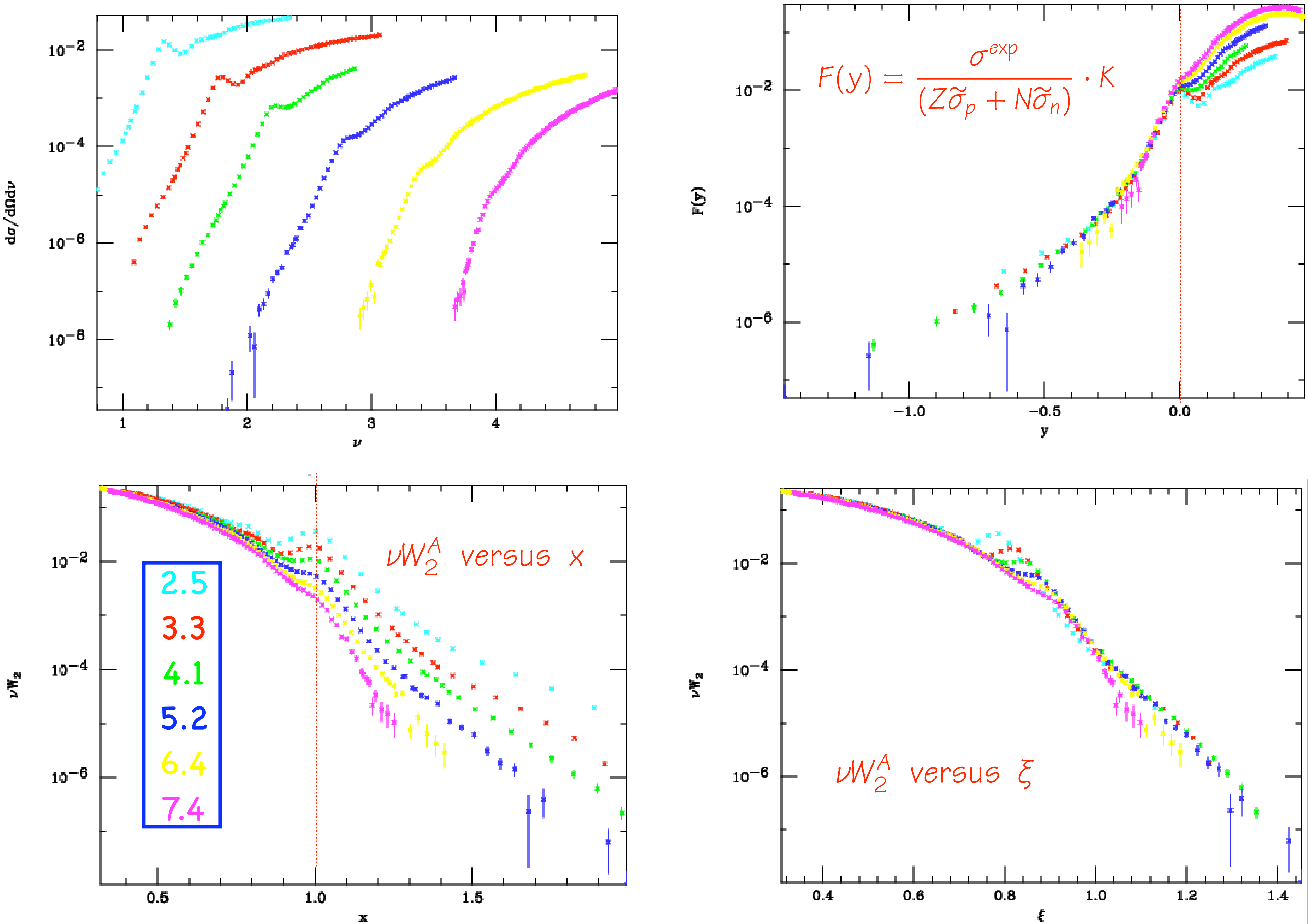
The Nachtmann variable (fraction ξ of nucleon light cone momentum p^+) has been shown to be the variable in which logarithmic violations of scaling in DIS should be studied.

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

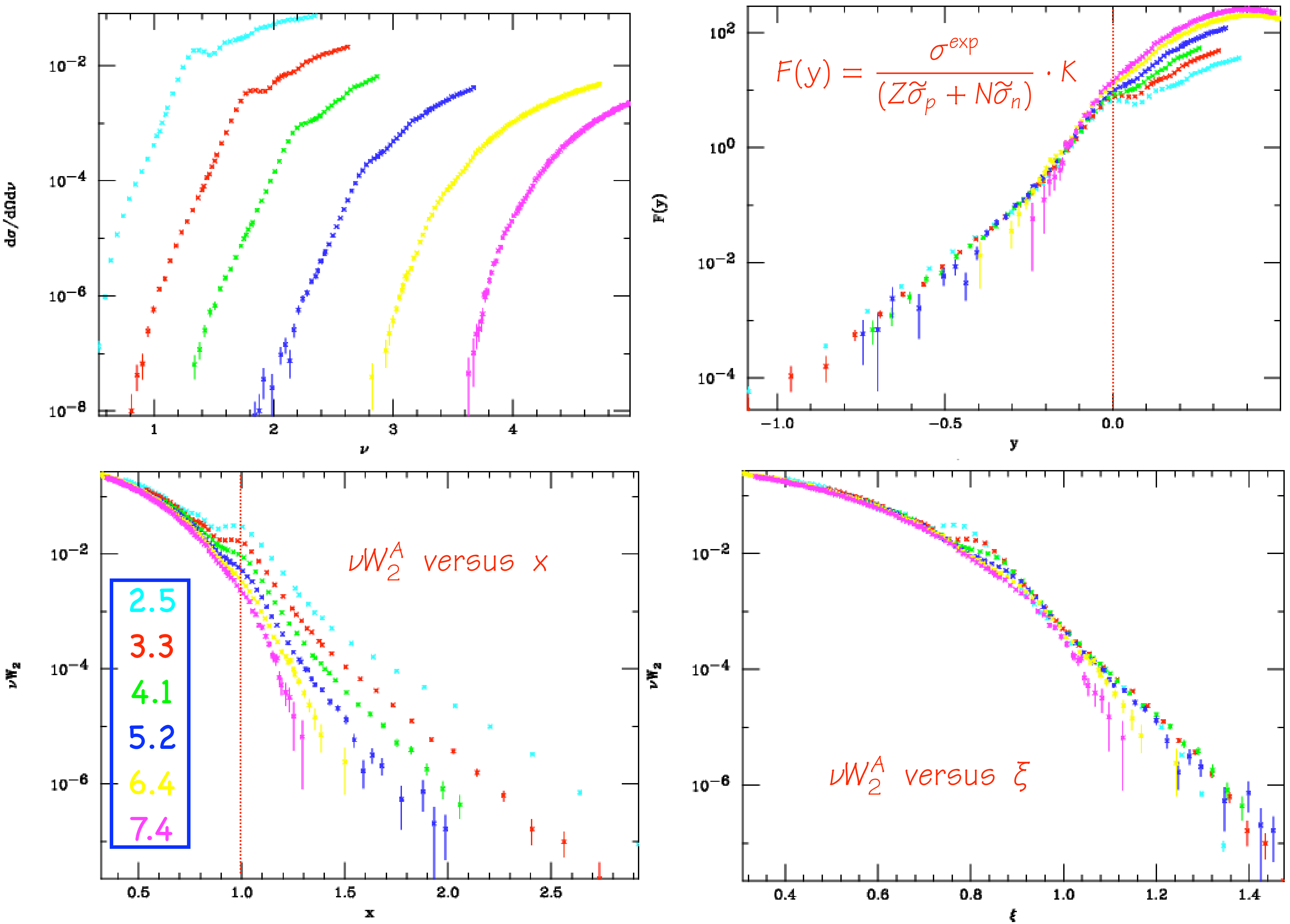
$$F_2^A(\xi) = \underbrace{\int_\xi^A dz F(z) F_2^n(\xi/z)}_{\text{averaging}}$$

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

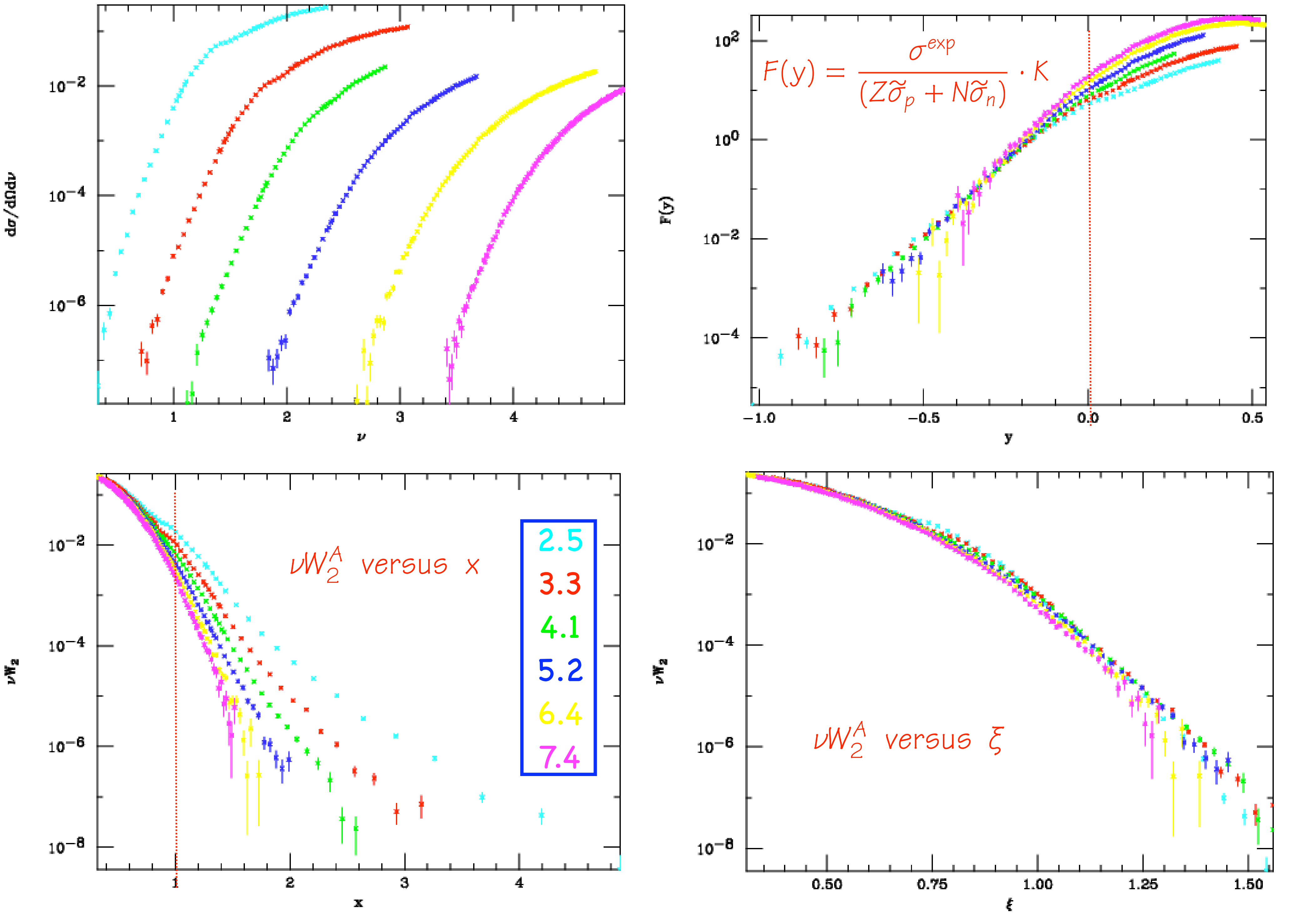
Preliminary Results - Deuteron



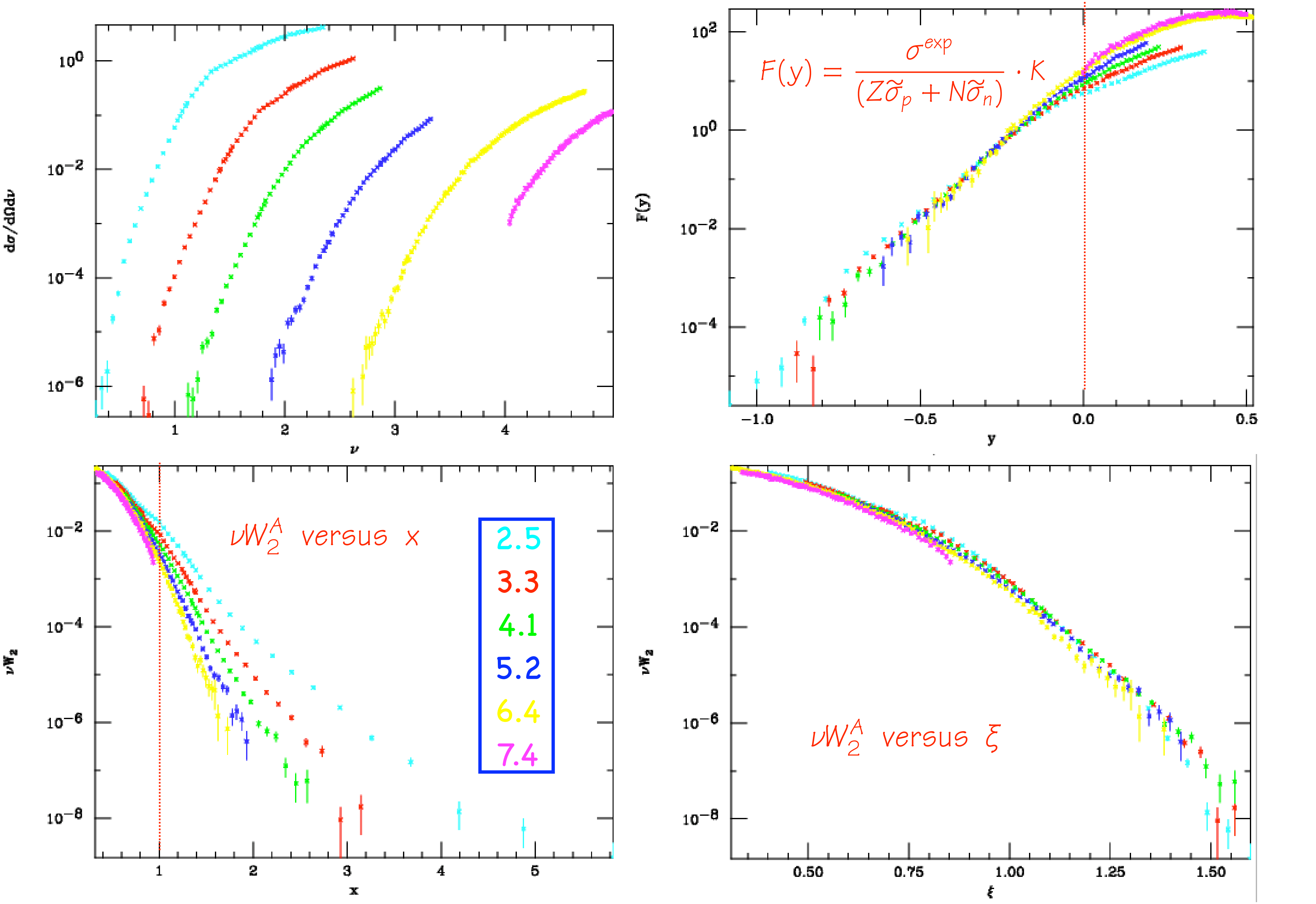
Preliminary Results - ^{3}He



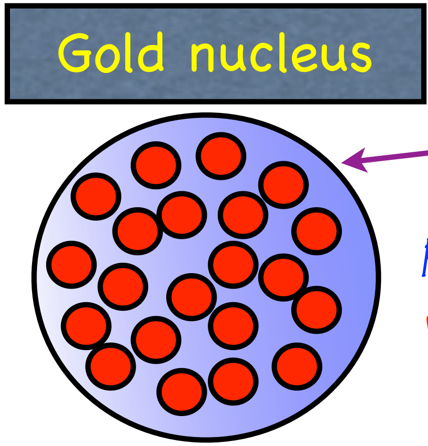
Preliminary Results - ^{12}C

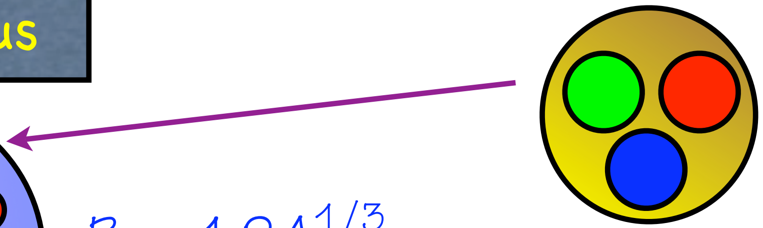


Preliminary Results - ^{197}Au



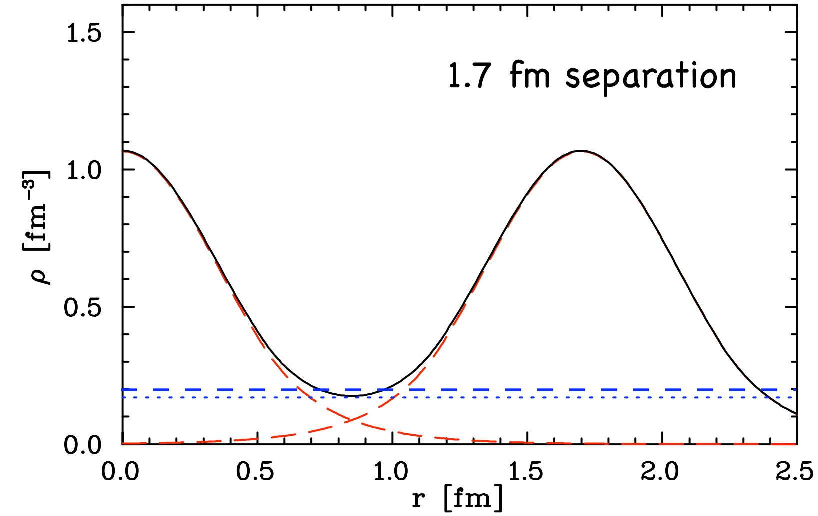
Medium Modifications generated by high density configurations





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

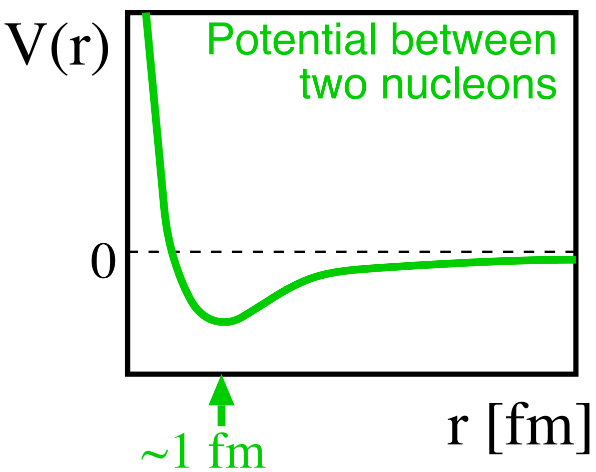
$Volume = \frac{4}{3}\pi R^3 \simeq 1400 fm^3$



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

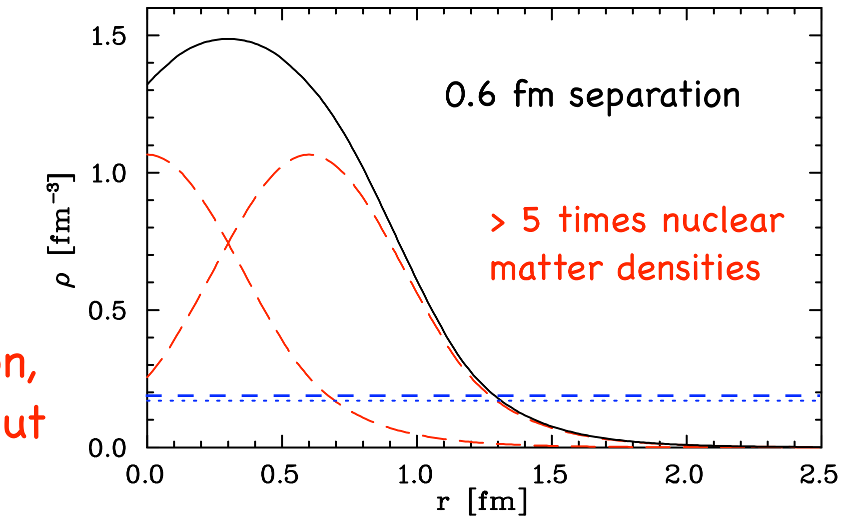
197 times 4.2 fm^3 ≈ 830 fm^3

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

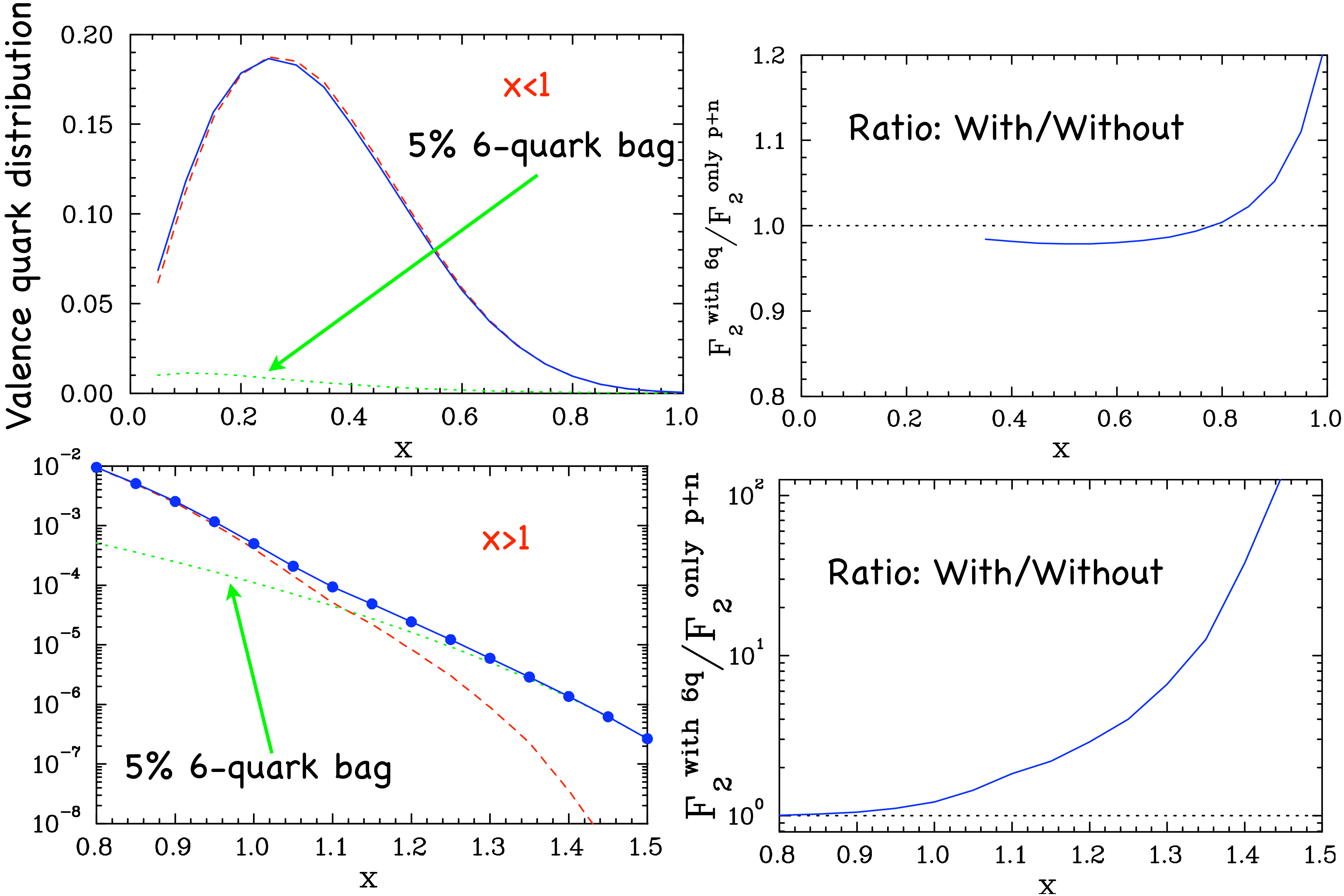


Comparable to neutron star densities!

High enough to modify nucleon structure?

To which nucleon does the quark belong?

Sensitivity to non-hadronic components



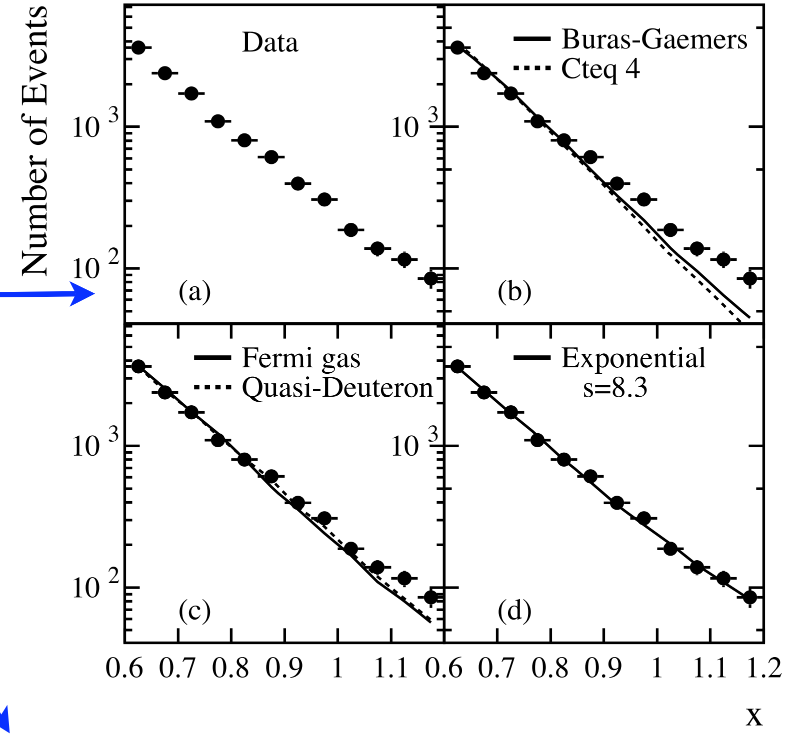
Mulders & Thomas

Quark distributions at x > 1

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

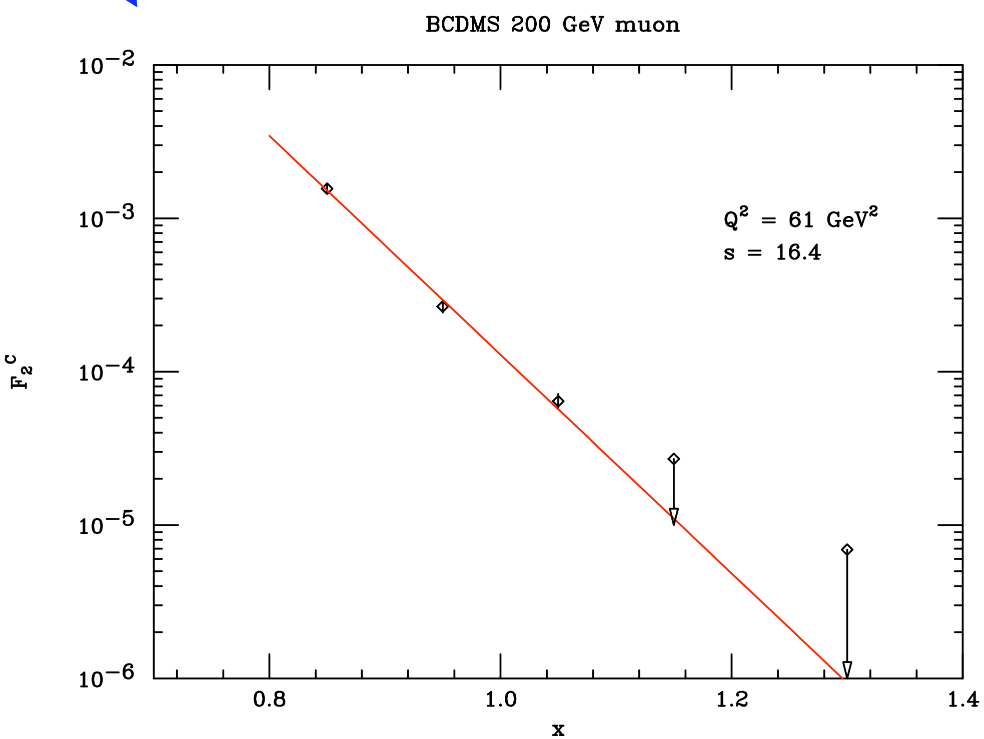
CCFR (ν-C): $F_2(x) \propto e^{-sx}$ s = 8

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



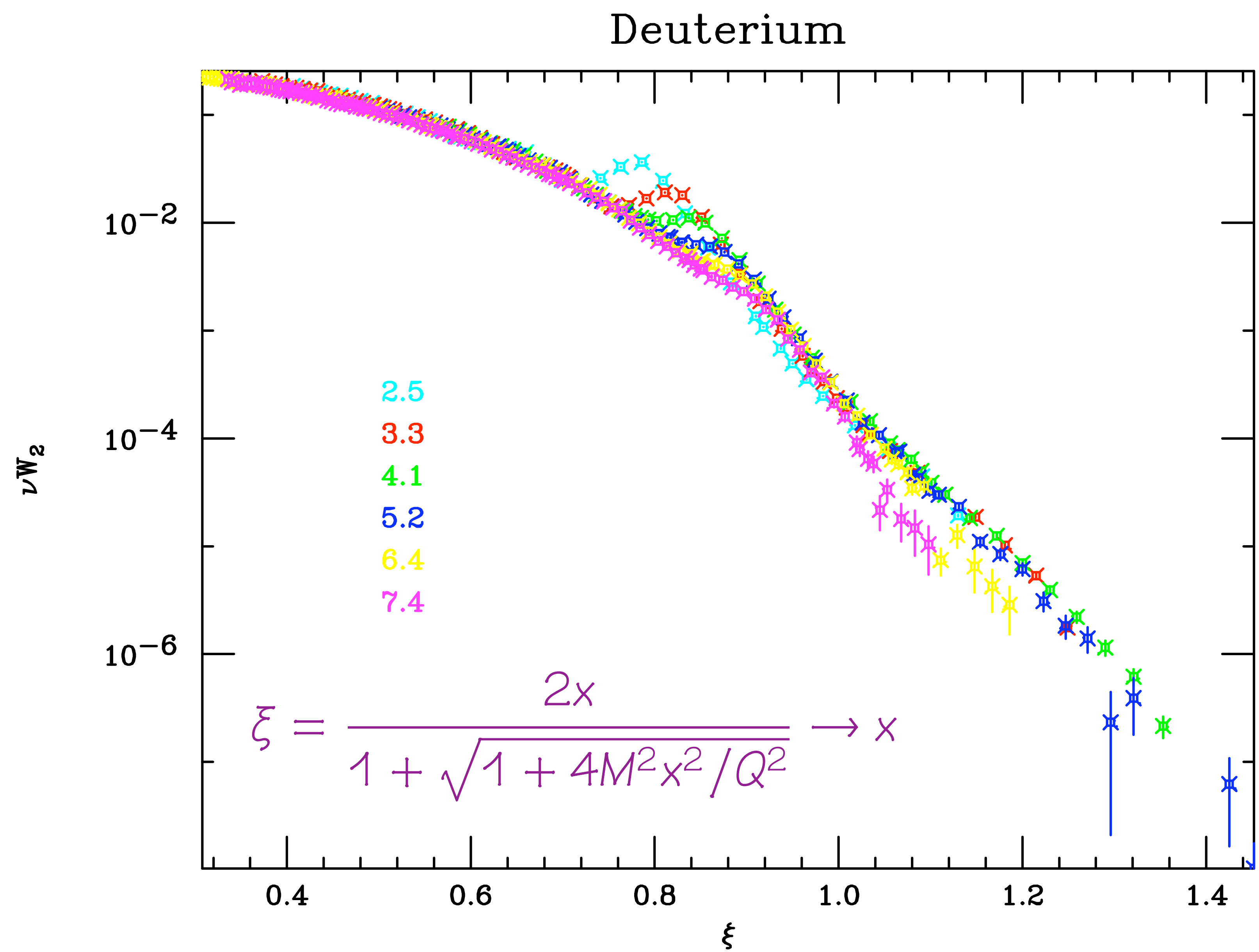
Limited x range, poor resolution

Limited x range, low statistics



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

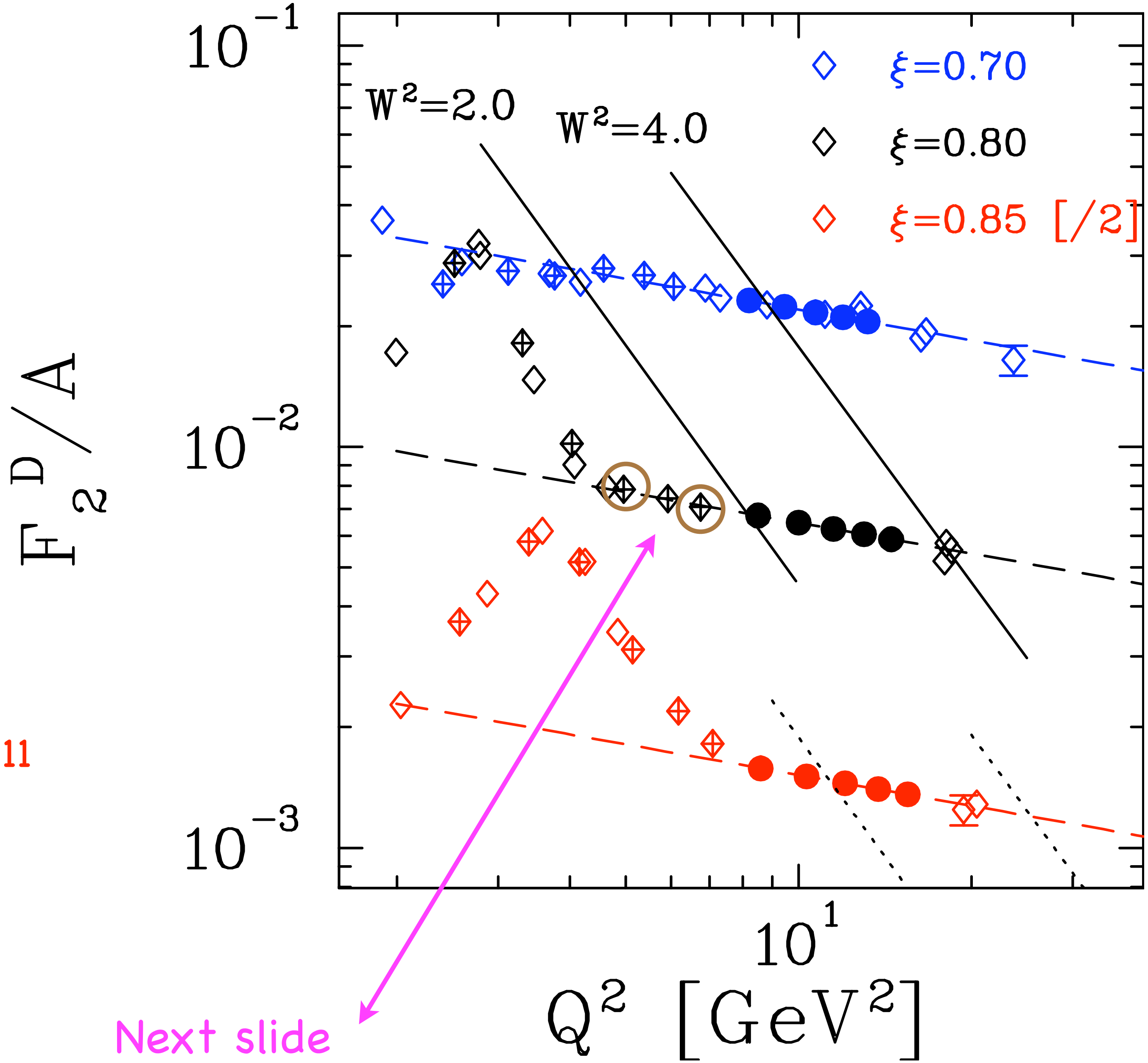
Quark Distribution Functions



νW_2^A versus ξ

Approach to Scaling - Deuteron

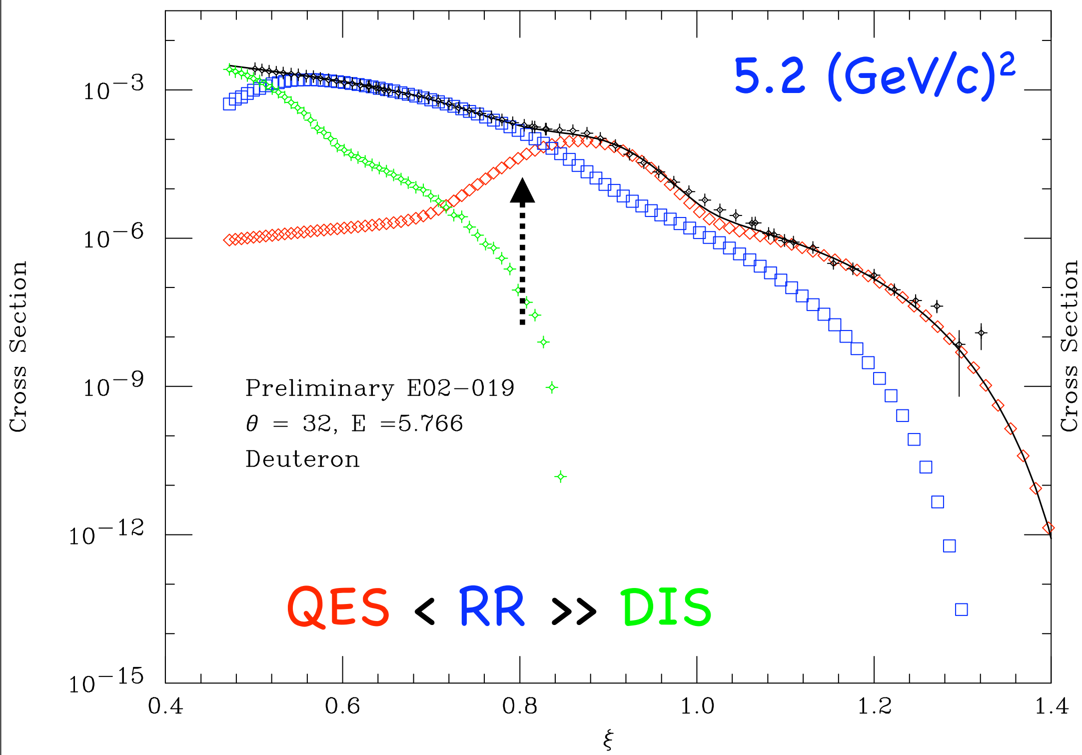
Dashed lines are arbitrary normalization (adjusted to go through the high Q^2 data) with a constant value of $d\ln(F_2)/d\ln(Q^2)$

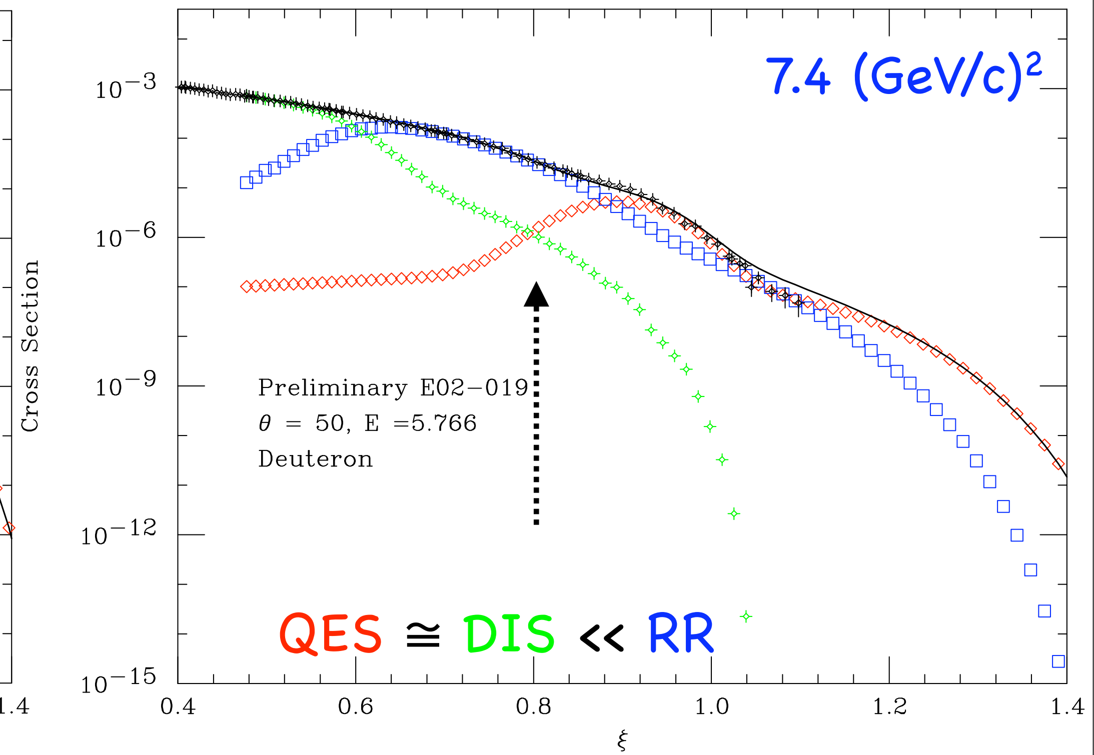


filled dots - experiment with 11 GeV

Next slide

Approach to Scaling (Deuteron)





Convolution model

QES

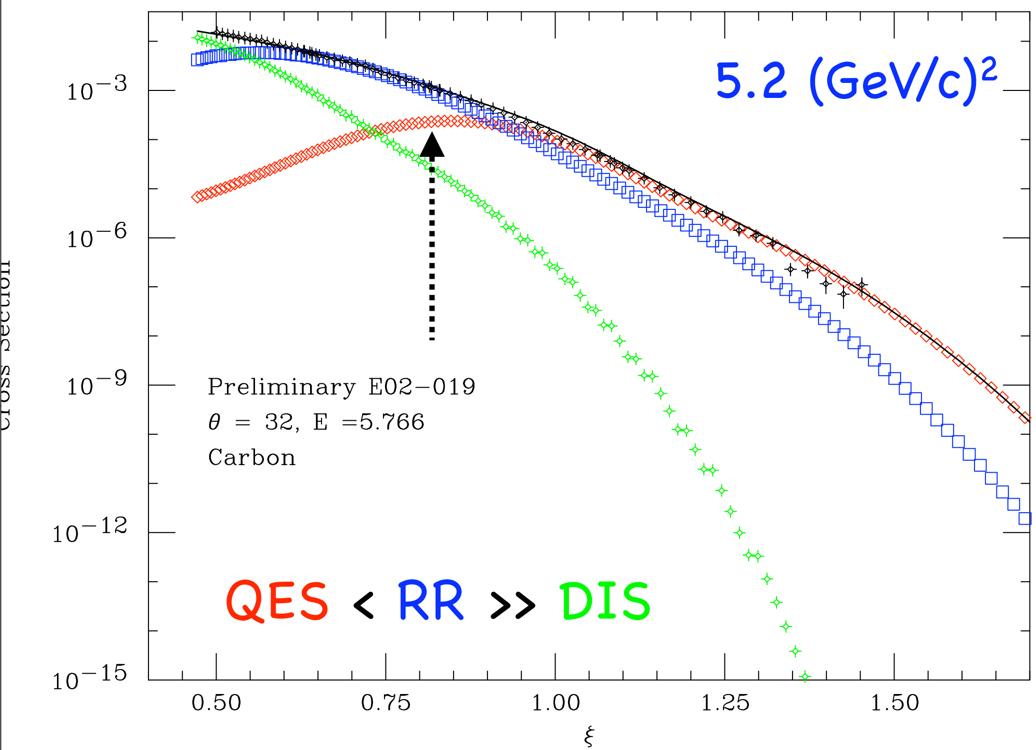
RR ($W^2 < 4$)

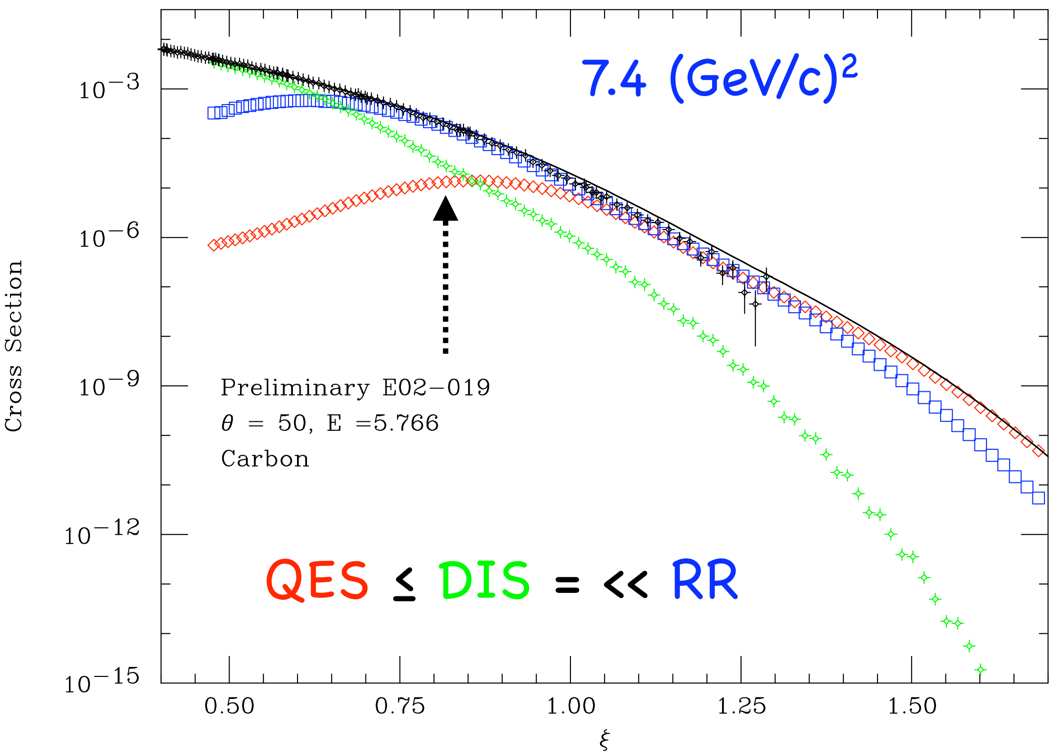
DIS ($W^2 > 4$)

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 ($W^2 < 4$)

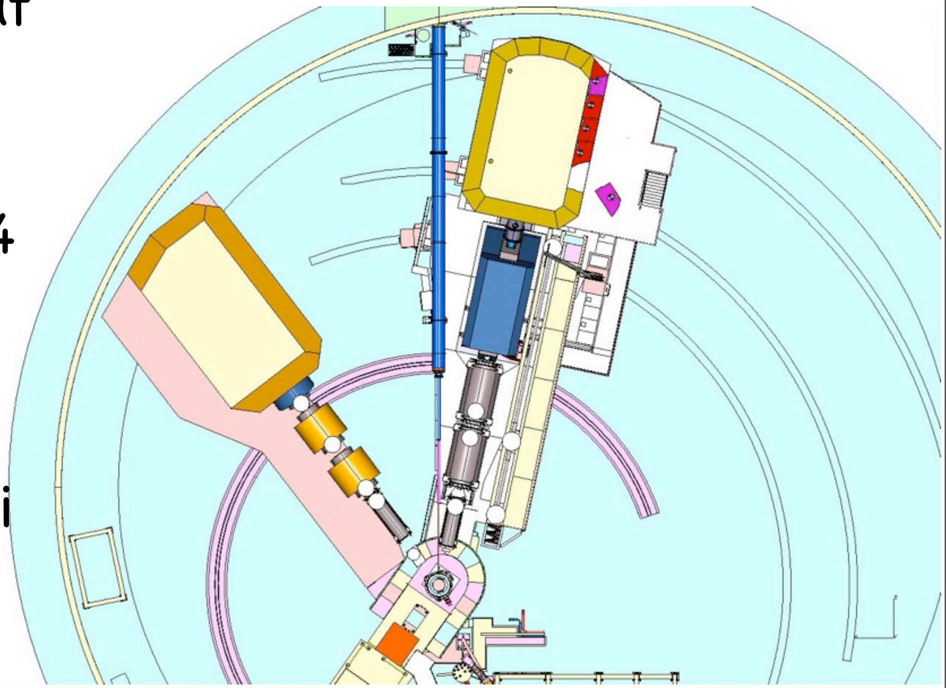
DIS ($W^2 > 4$)

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

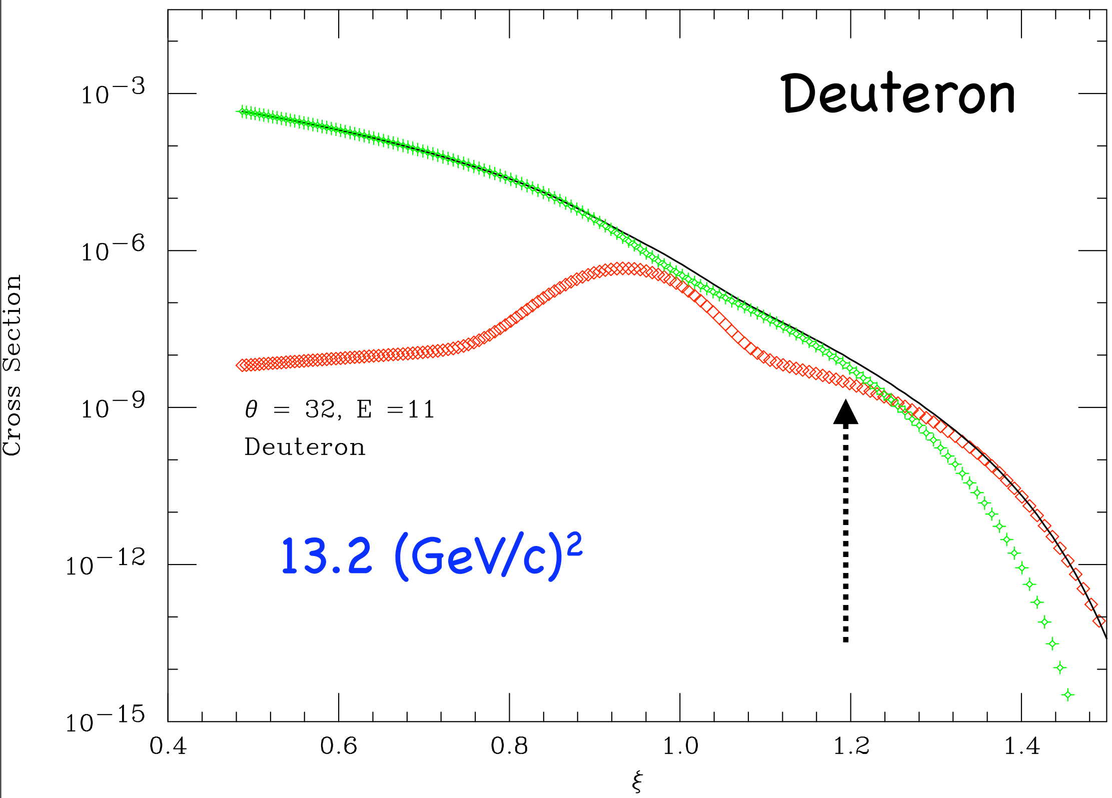
Inclusive DIS at $x > 1$ at 12 GeV

- New proposal approved at last JLAB PAC
- 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 $x = 1.5$



Quark distributions at x > 1

Predictions for 11 GeV

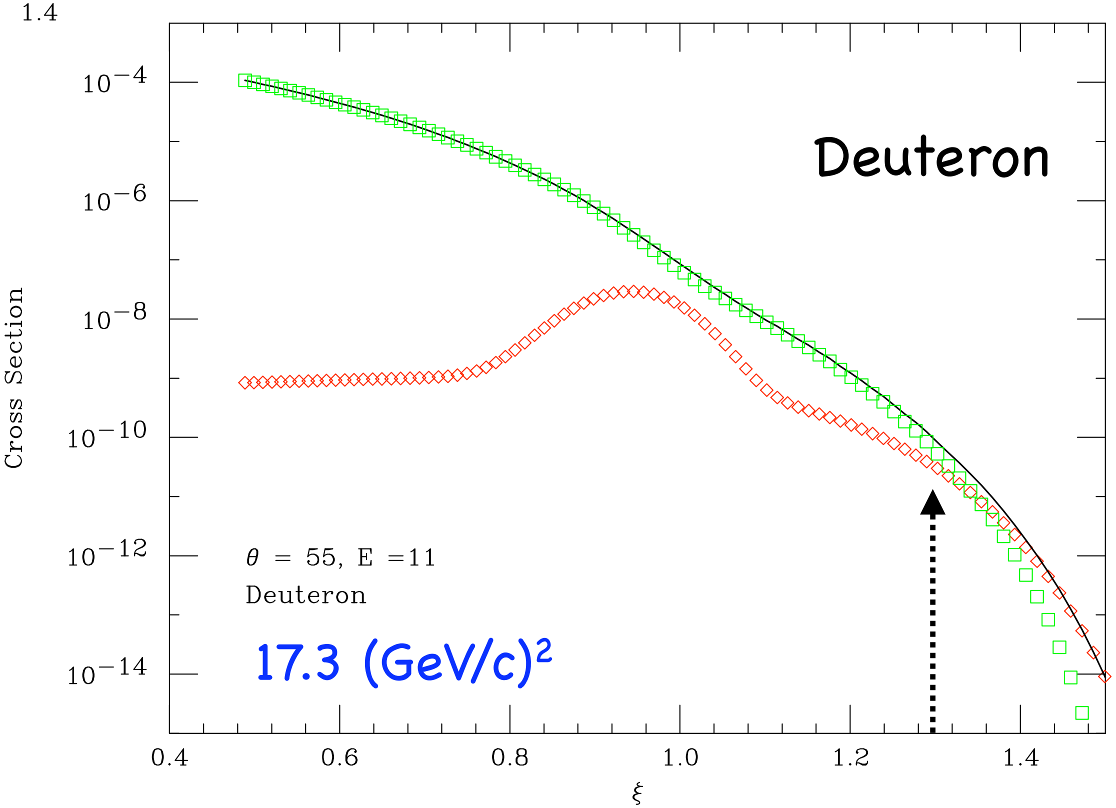


Convolution model

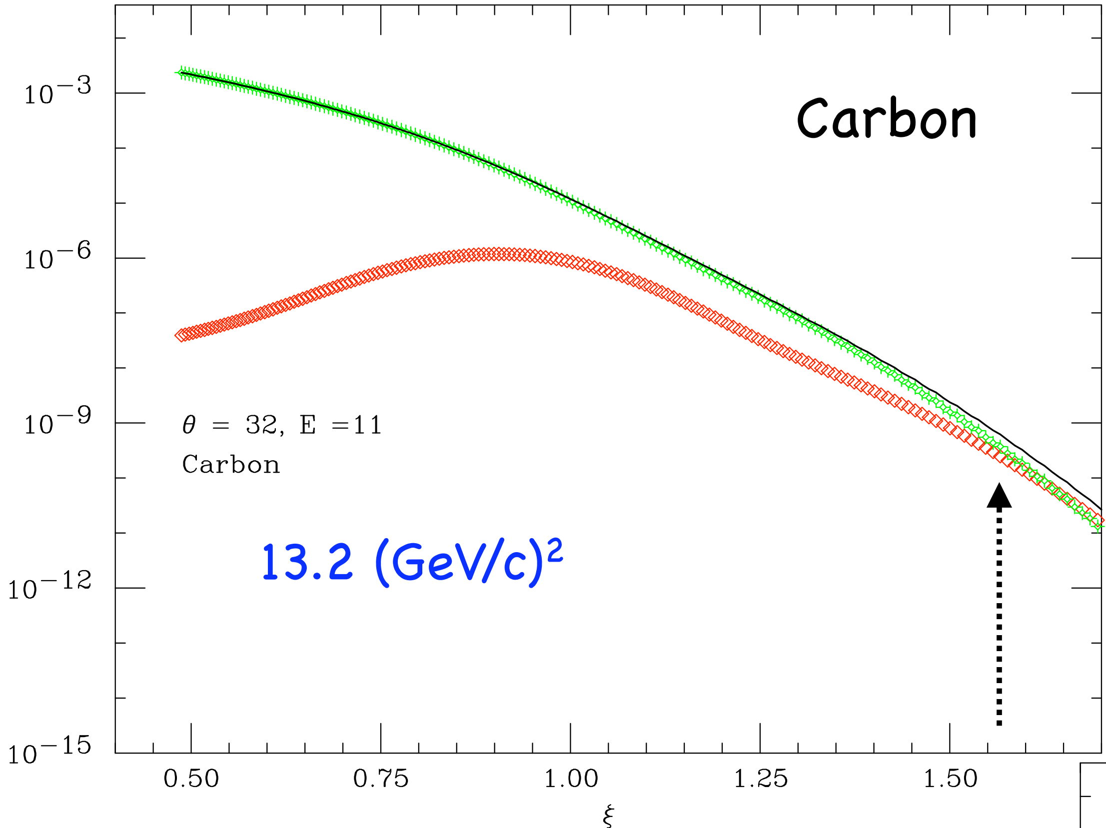
QES

DIS + RR

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



Quark distributions at x > 1

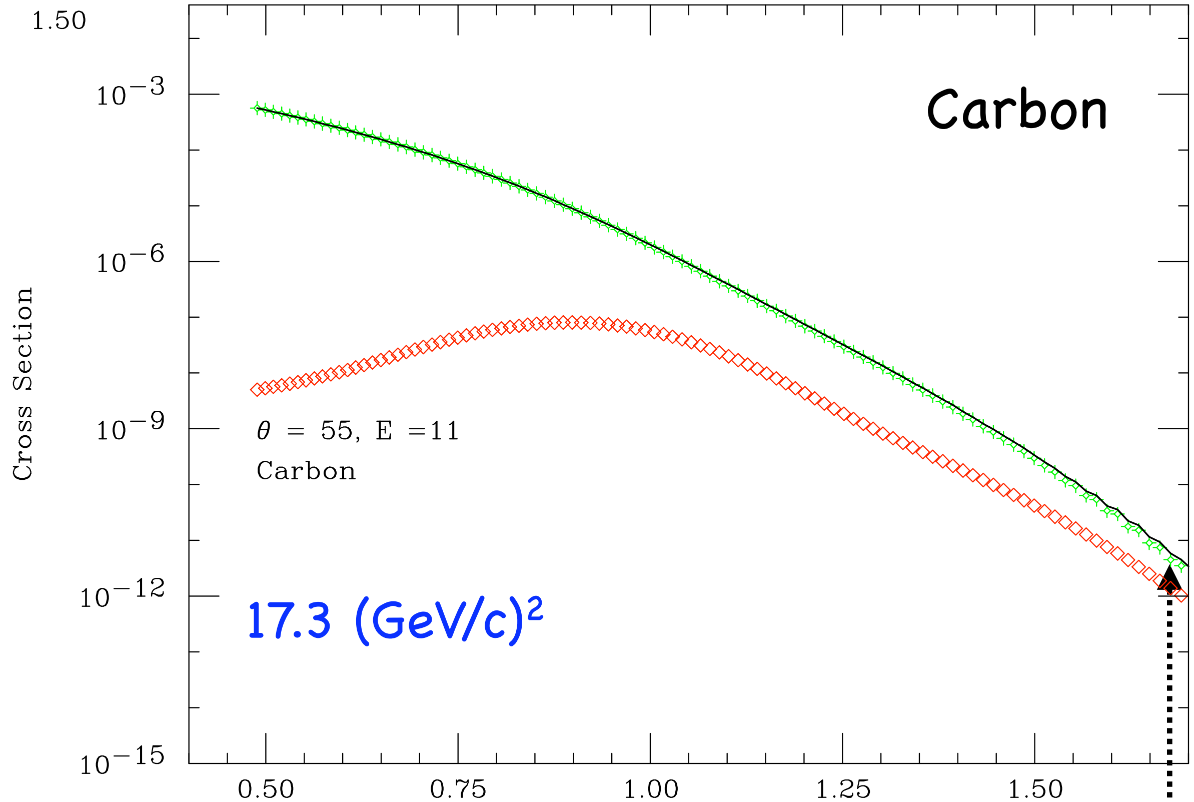


Predictions for 11 GeV

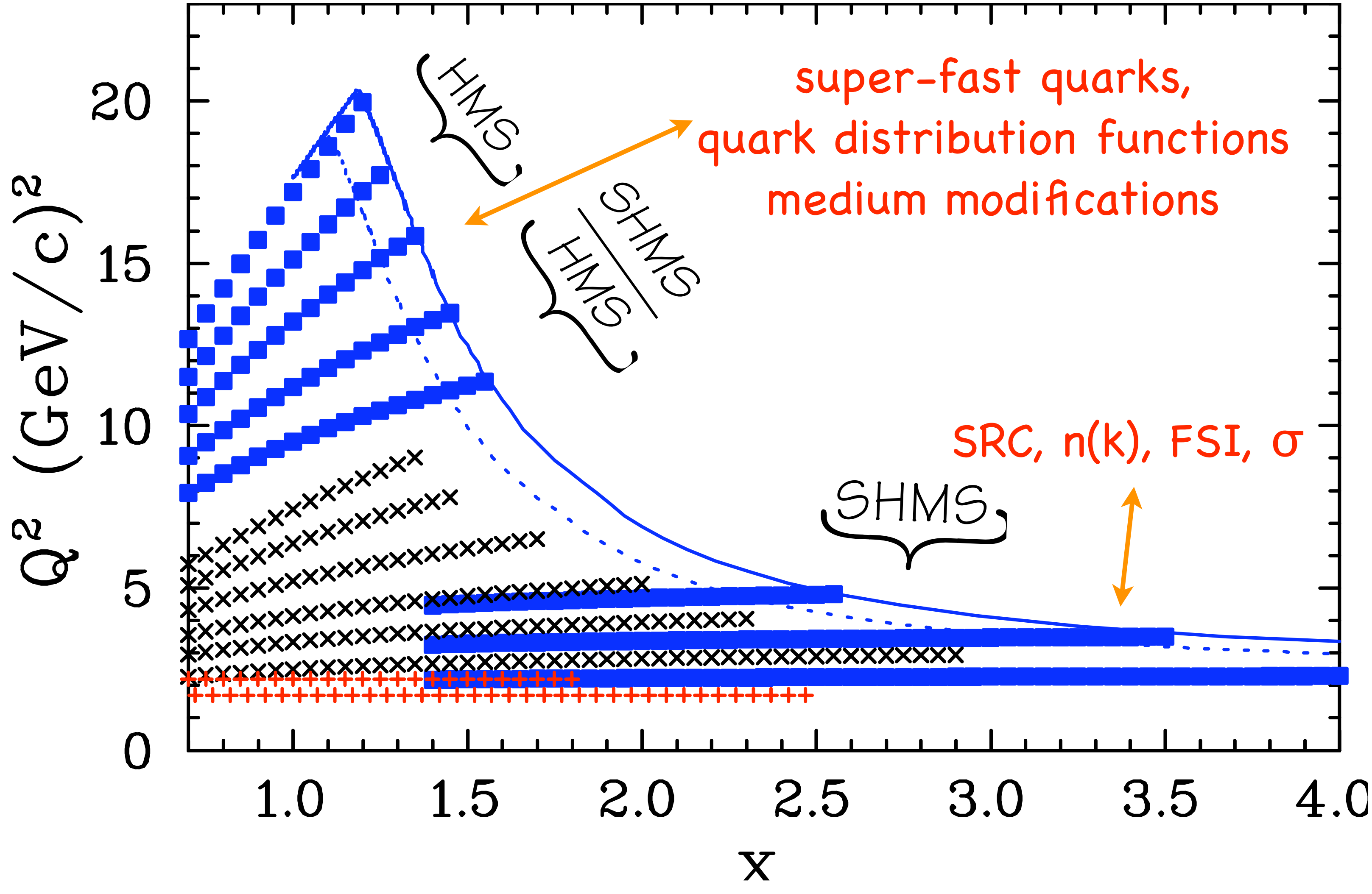
Convolution model

QES

DIS + RR



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
- Moment analysis of structure functions
- DIS is does not dominate over QES at 6 GeV but should be at 11 GeV and at $Q^2 > 10 - 15$ $(GeV/c)^2$.
- Experiments are relatively straightforward. JLAB at 12 GeV will significantly expand the coverage in x-Q^2

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

- Home page
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- Utilities
- Bibliography
- 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

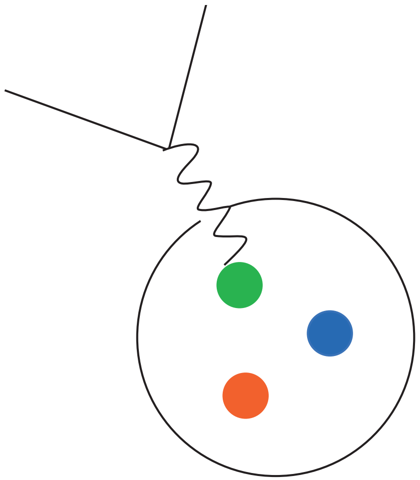
At present there are about 600 different combinations of targets, energies and angles consisting of some 19,000 data points.

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.

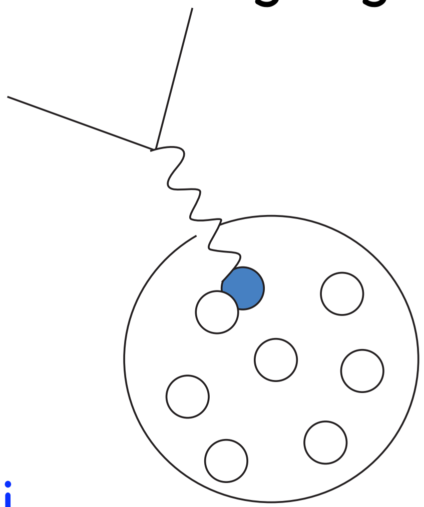
If you wish to be alerted to changes in the archive or to the inclusion of new data, send an email to me. Send any comments or corrections you might have as well.

Short Range Correlations



For a nucleon at rest, $x < 1$
as $x = 1$ is the elastic limit

For e-A scattering x is not so restricted; $x > j-1$
where j is the number of nucleons coming together.
Recall for $k = k_F$, $x \leq 1.2$.



$x > 1 \Rightarrow$ 2 nucleons close together

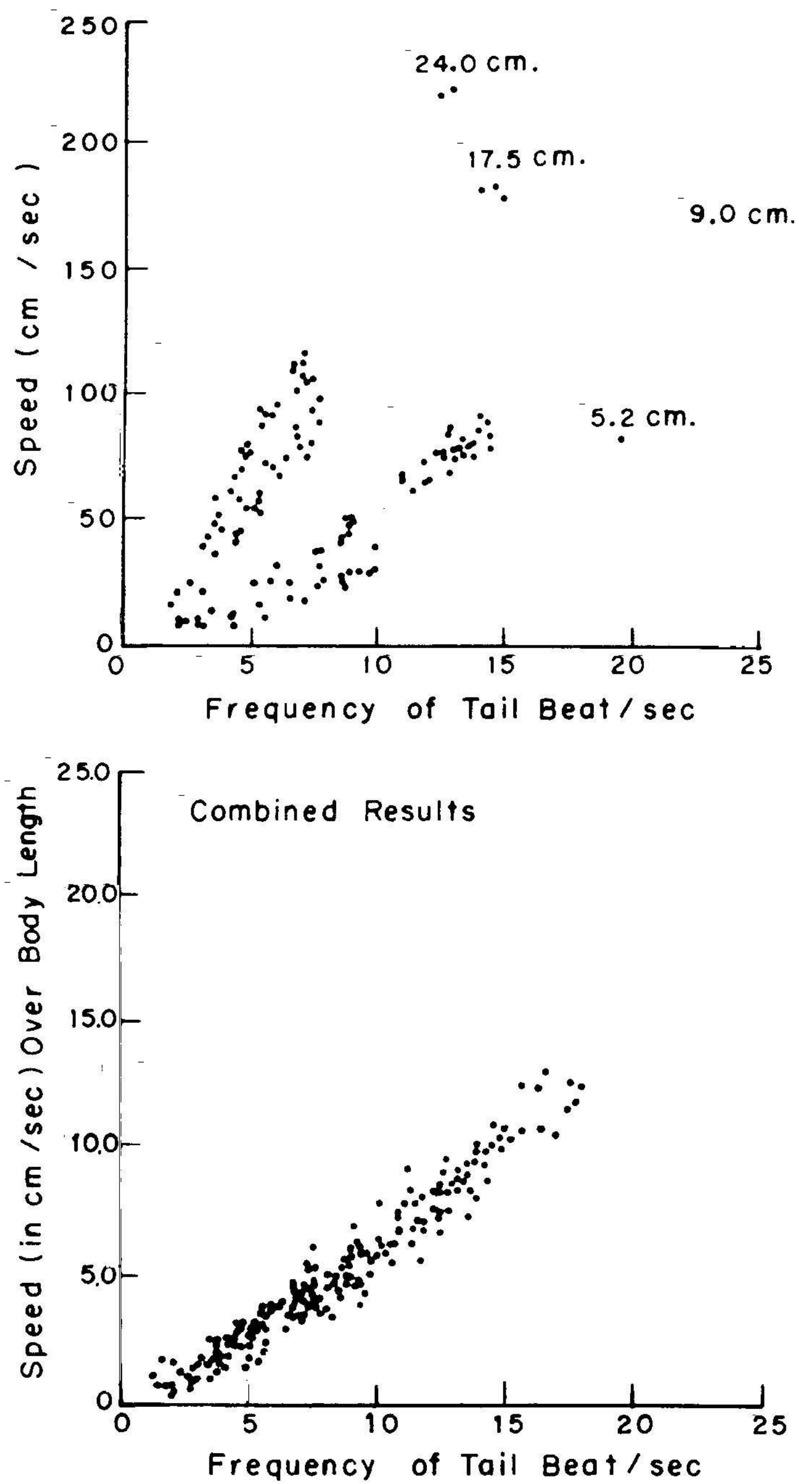
$x > 2 \Rightarrow$ 3 nucleons close together

Further, when j nucleons are close together the A-j nucleons have little influence.

The Spectral Function with a high-k nucleon can be represented as a sum over 2,3 ... nucleon correlations; one must account for the CM motion of the correlation.

Scaling in Nature

Swimming speed of a fresh water fish, the dace.



Scaling: Why is animal size so important?
Kurt Schmidt Nielsen

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.

Parton Recombination

- Explicit calculable mechanism to account for short range modification of nucleons structure in nucleus.
- Partons can recombine or fuse with partons of a neighboring nucleon to form a single parton with the sum of the initial momenta.
- Initial state recombination populates the x>1 region with quarks that have absorbed momentum from neighboring gluons
- Modification to the valence parton distribution, and the nonsinglet part of F_2^N is determined by

$$\begin{aligned}
\Delta V(x, Q^2) \quad &= \quad \frac{3}{2} R_A \tilde{n}_A \frac{4\pi\alpha_s(Q^2)}{Q^2} \\
&\times \left[\int_x^1 dy V(y) G(x-y) \Gamma_{qq}(y, x-y, x) \right. \\
&\left. - V(x) \int_0^1 dy G(y) \Gamma_{qq}(x, y, x+y) \right]
\end{aligned}$$

Inelastic contribution to $\bar{F}_2(x, Q^2)$

And a calculation of the parton recombination modification (dotted) for $Q_0 = 1\ \mathrm{GeV}^2$. The dashed line indicates the free nucleon structure function.