Electron scattering from nuclei in the quasielastic region and beyond

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University of Virginia

Part 2

HUGS 2007

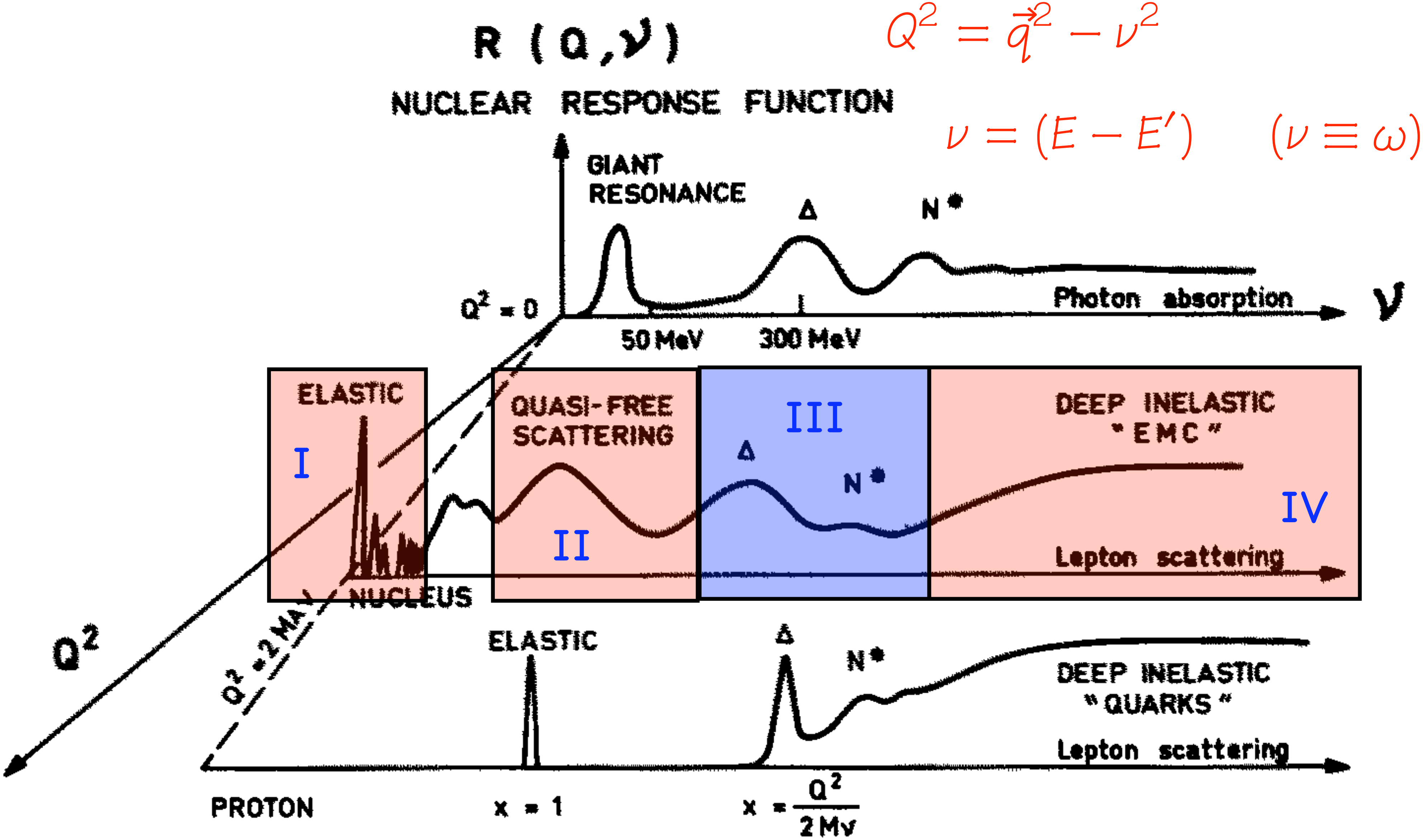
June 2007

Newport News, VA

Nuclear Response Function

$$Q^2 = \vec{q}^2 - \nu^2$$

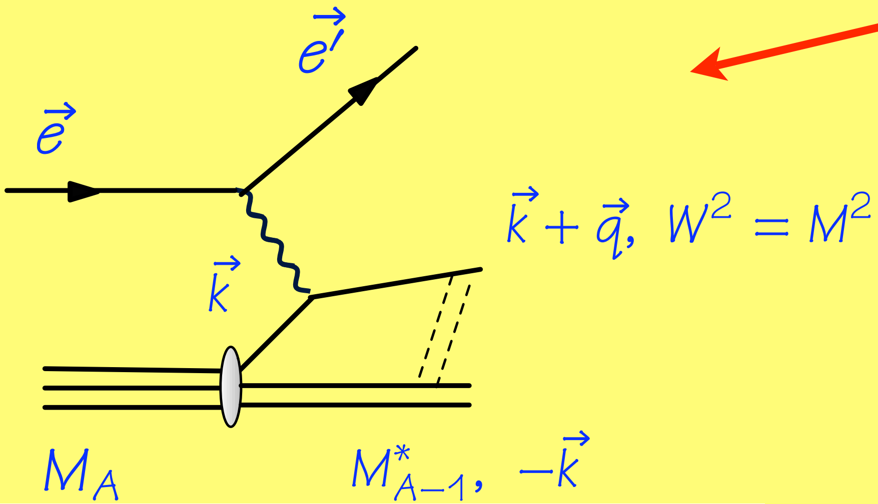
$$\nu = (E - E') \qquad (\nu \equiv \omega)$$

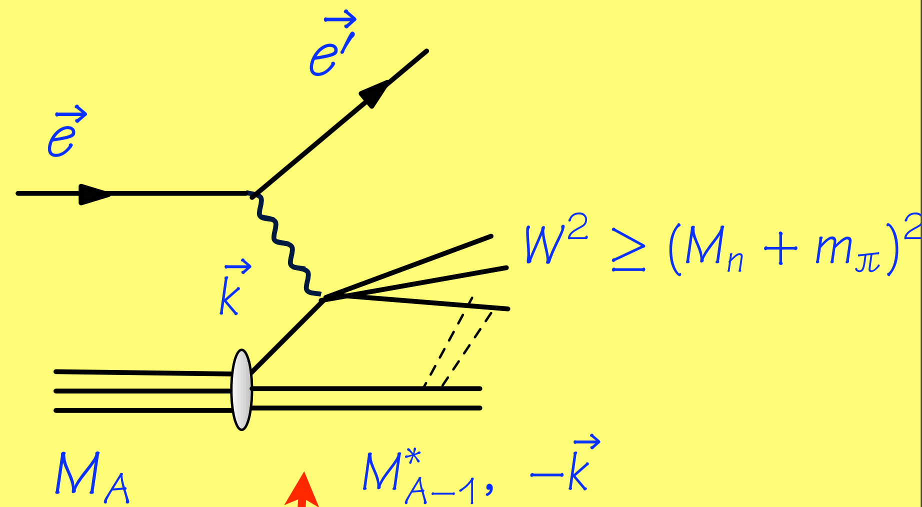


Inclusive Electron Scattering from Nuclei

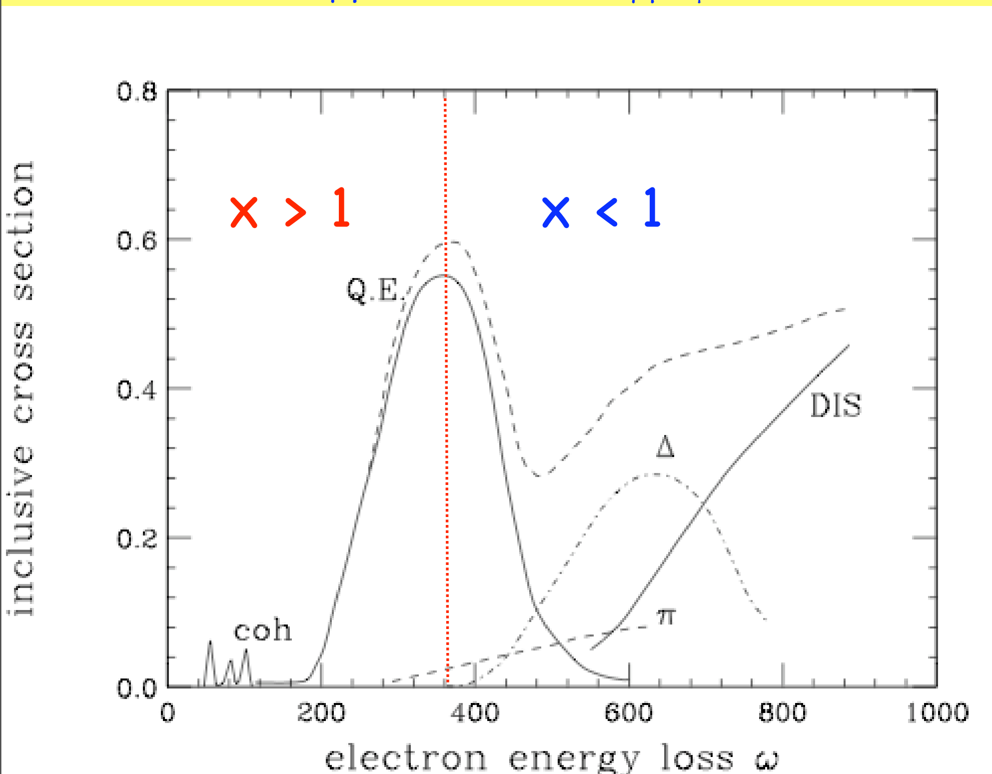
Two distinct processes

Quasielastic from the nucleons in the nucleus





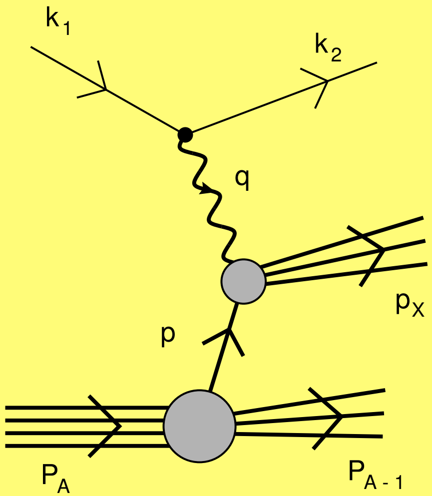
Inelastic and DIS from the quark constituents of the nucleon.



Inclusive final state means no separation of two dominant processes

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

υ,ω=energy loss



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 IA

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

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 $\ln Q^2$ dependence

Exploit this dissimilar Q^2 dependence

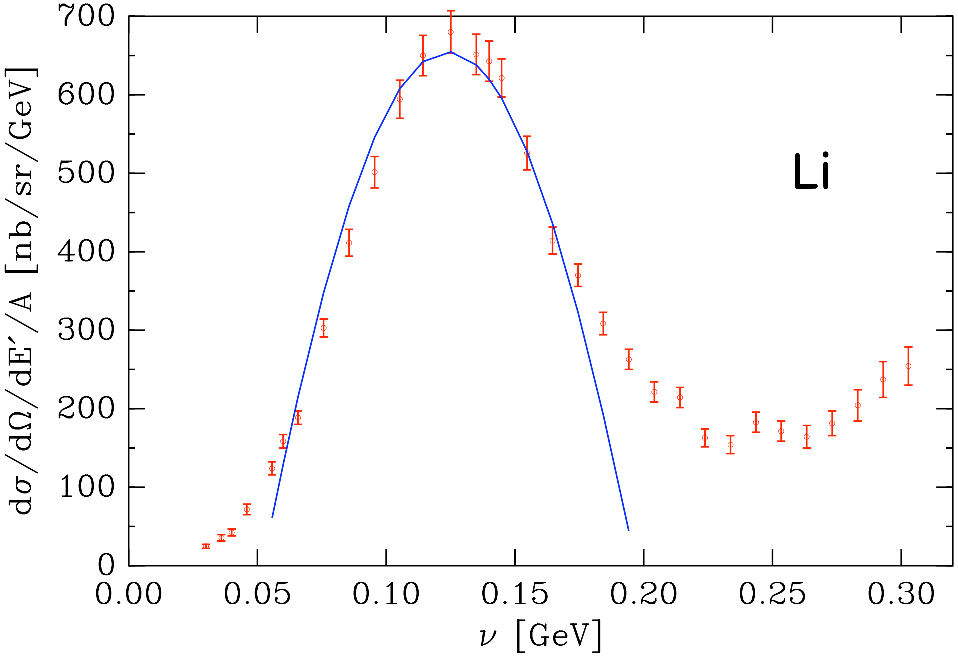
Early 1970's Quasielastic Data

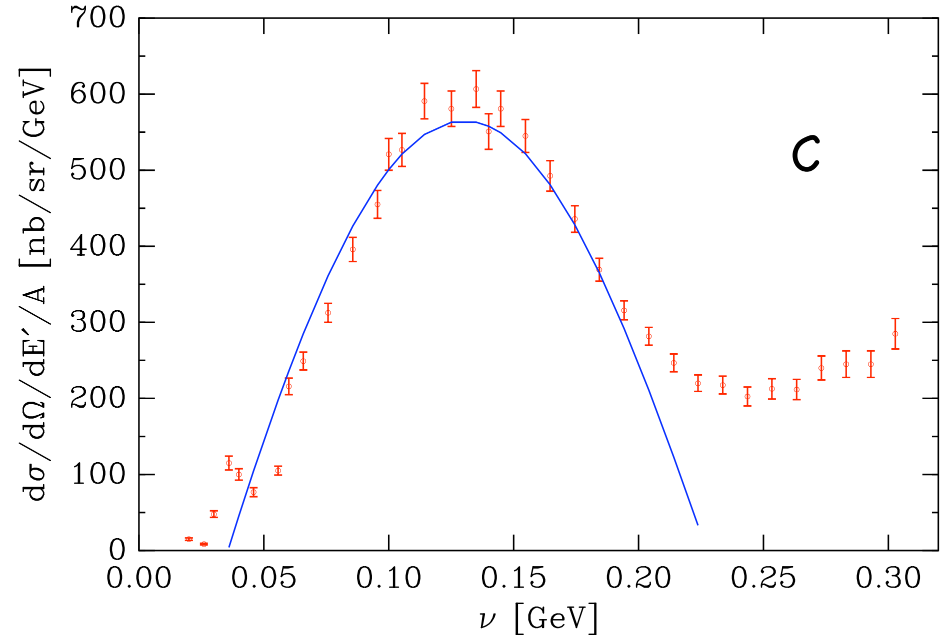
-> getting the bulk features

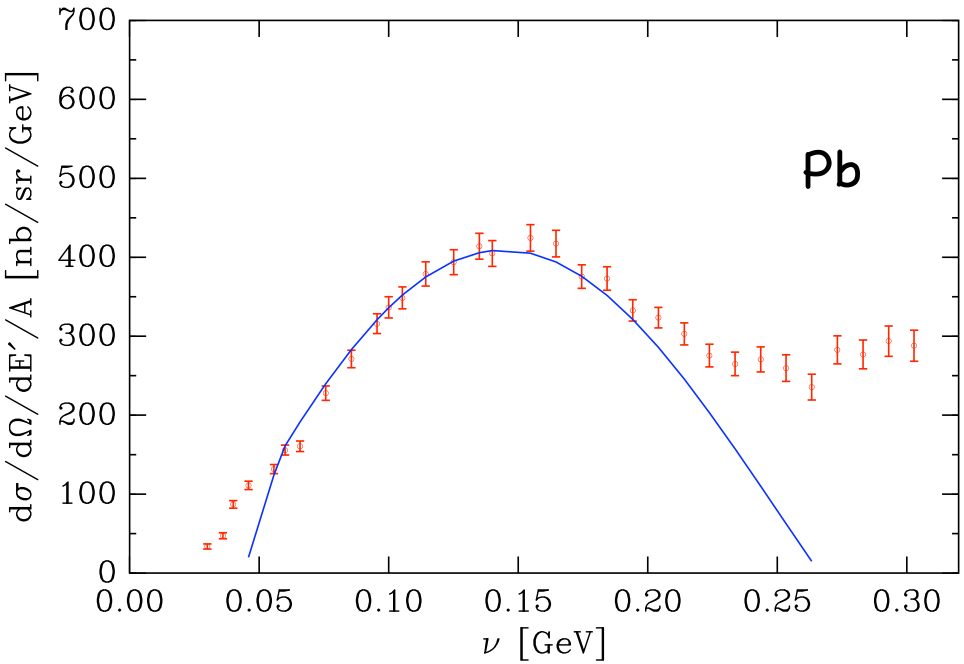
500 MeV, 60 degrees

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

R.R. Whitney et al., Phys. Rev. C 9, 2230 (1974).

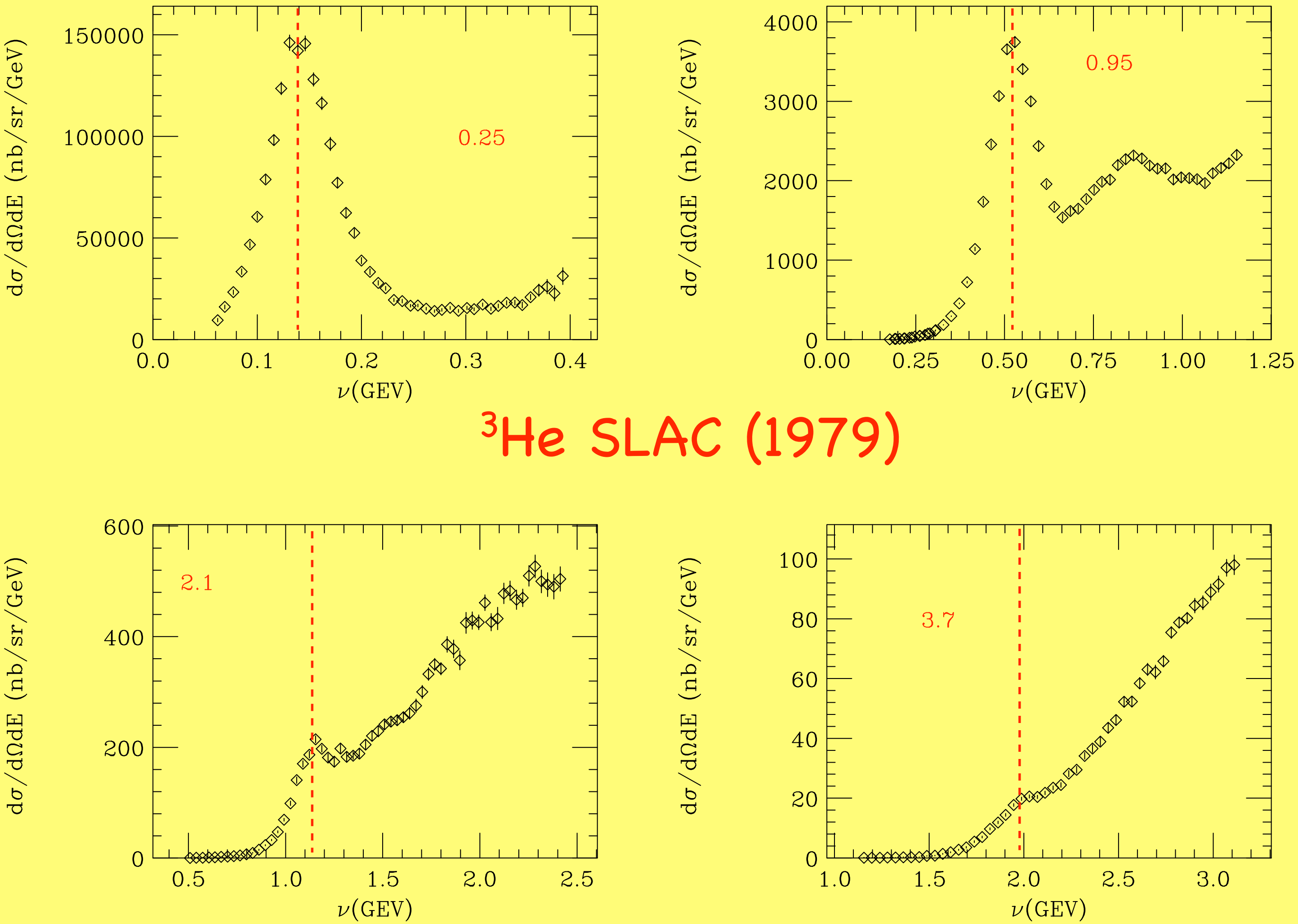






Nucleus	k_F	$\bar{\epsilon}$
^{6}Li	169	17
^{12}C	221	25
^{24}Mg	235	32
^{40}Ca	251	28
^{nat}Ni	260	36
^{89}Y	254	39
^{nat}Sn	260	42
^{181}Ta	265	42
^{208}Pb	265	44

compared to Fermi model: fit parameter k_F and ϵ

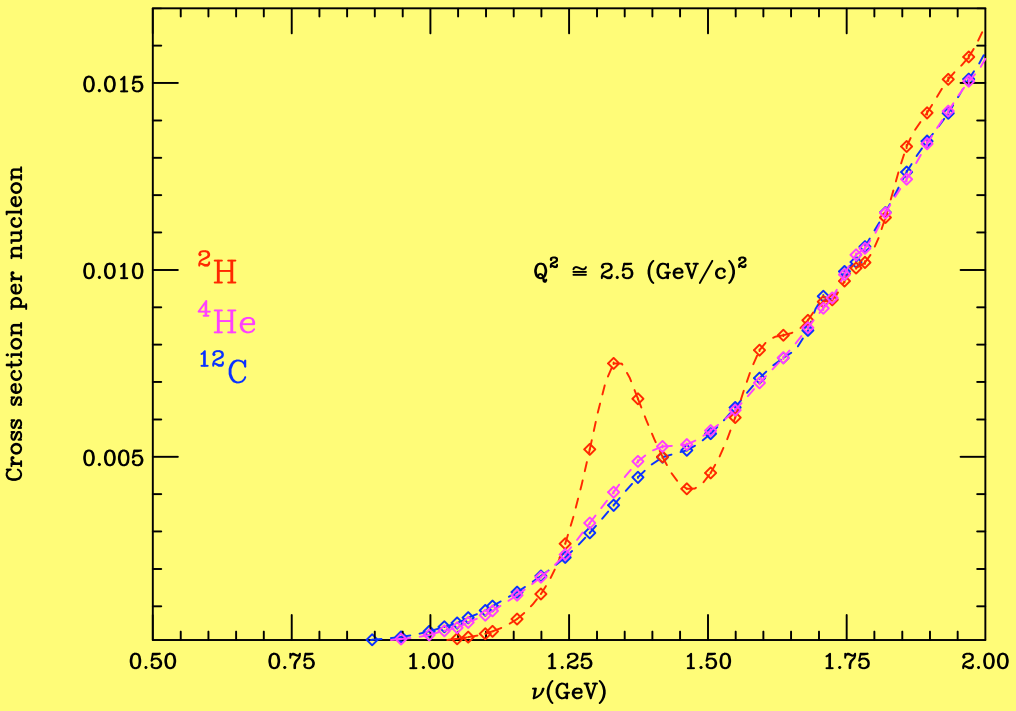


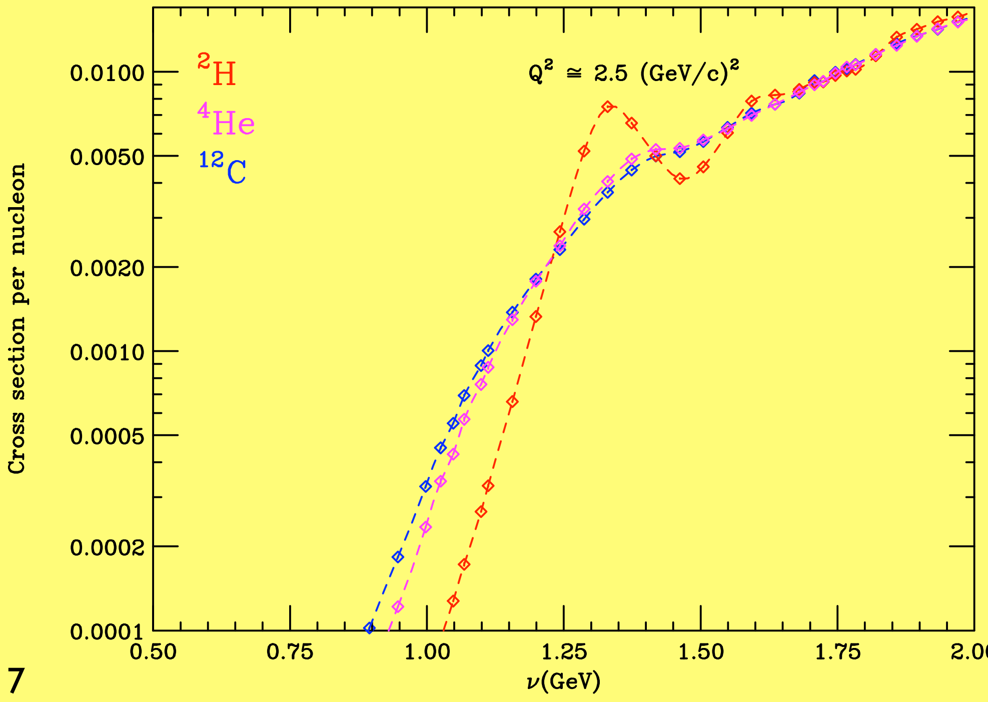
The quasielastic peak (QE) is broadened by the Fermi-motion of the struck nucleon.

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





Scaling

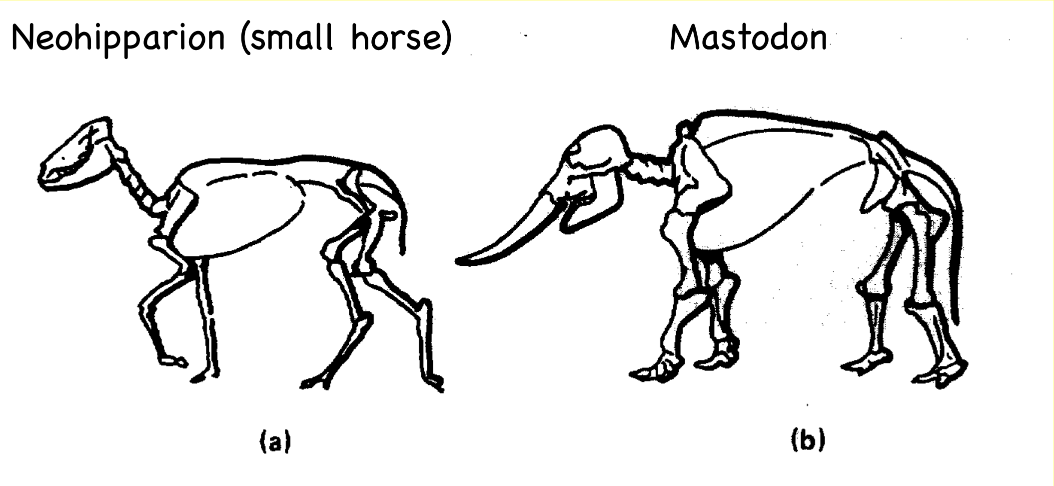
- Scaling refers to the dependence of a cross section, in certain kinematic regions, on a single variable. If the data scales in the single variable then it validates the assumptions about the underlying physics and scale-breaking provides information about conditions that go beyond the assumptions.

- 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.

- 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.

Classical Scaling

Galileo realized that that if one simply scaled up an animals size its weight would increase significantly faster than its strength, "....you can plainly see the impossibility of increasing the size of structures to vast dimensions...if his height be increased inordinately, he will fall and be crushed under his own weight"



$$\frac{Strength}{Weight} \propto \frac{A}{V} \propto \frac{1}{l} \propto \frac{1}{W^{1/3}}$$

Smaller animals appear stronger

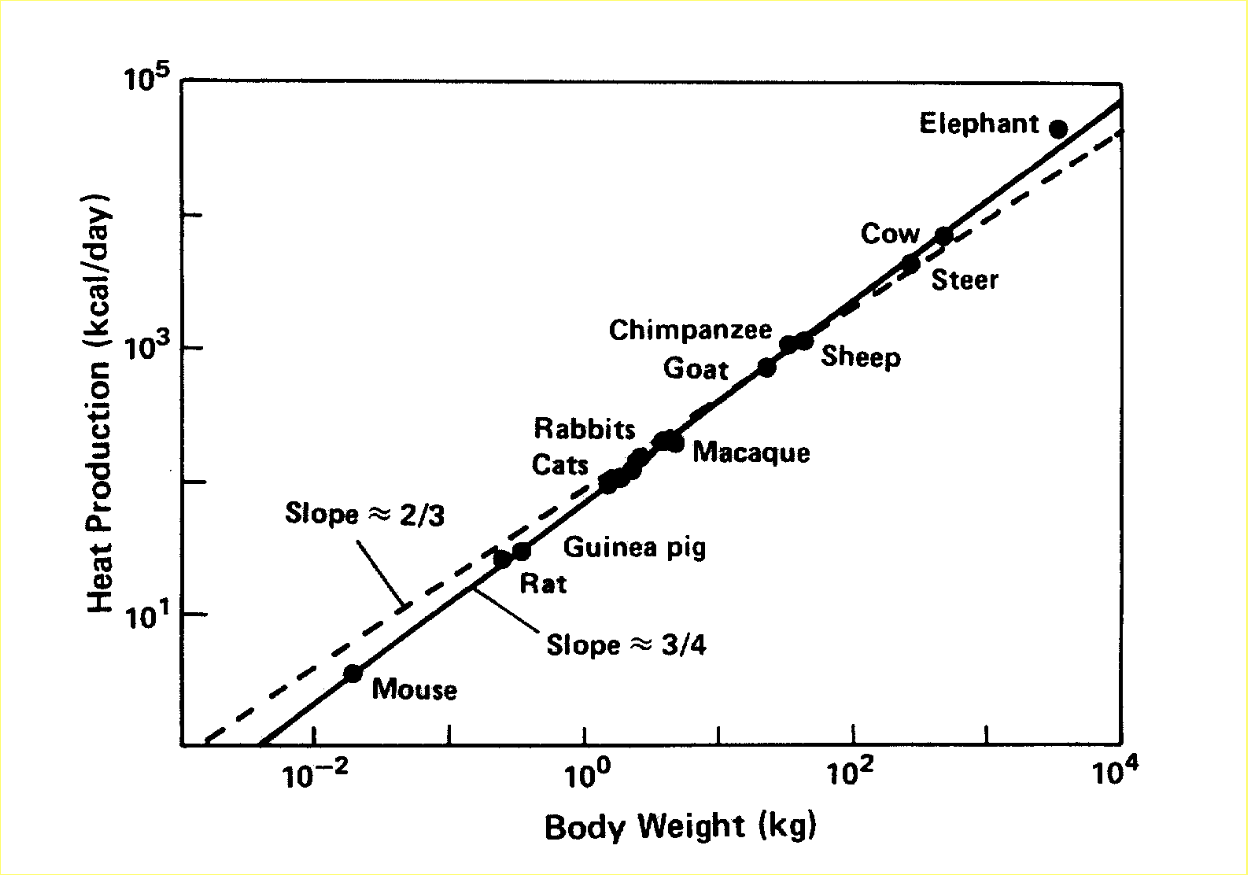
Explains why small animals can leap as high as large one ...

G. West, LANL report

Metabolism

- How does the metabolic rate (B) vary from animal to animal?
- B = heat lost by a body in steady inactive state
  - Should be dominated by the surface affects of sweating and radiation

$$B \propto W^{2/3}$$



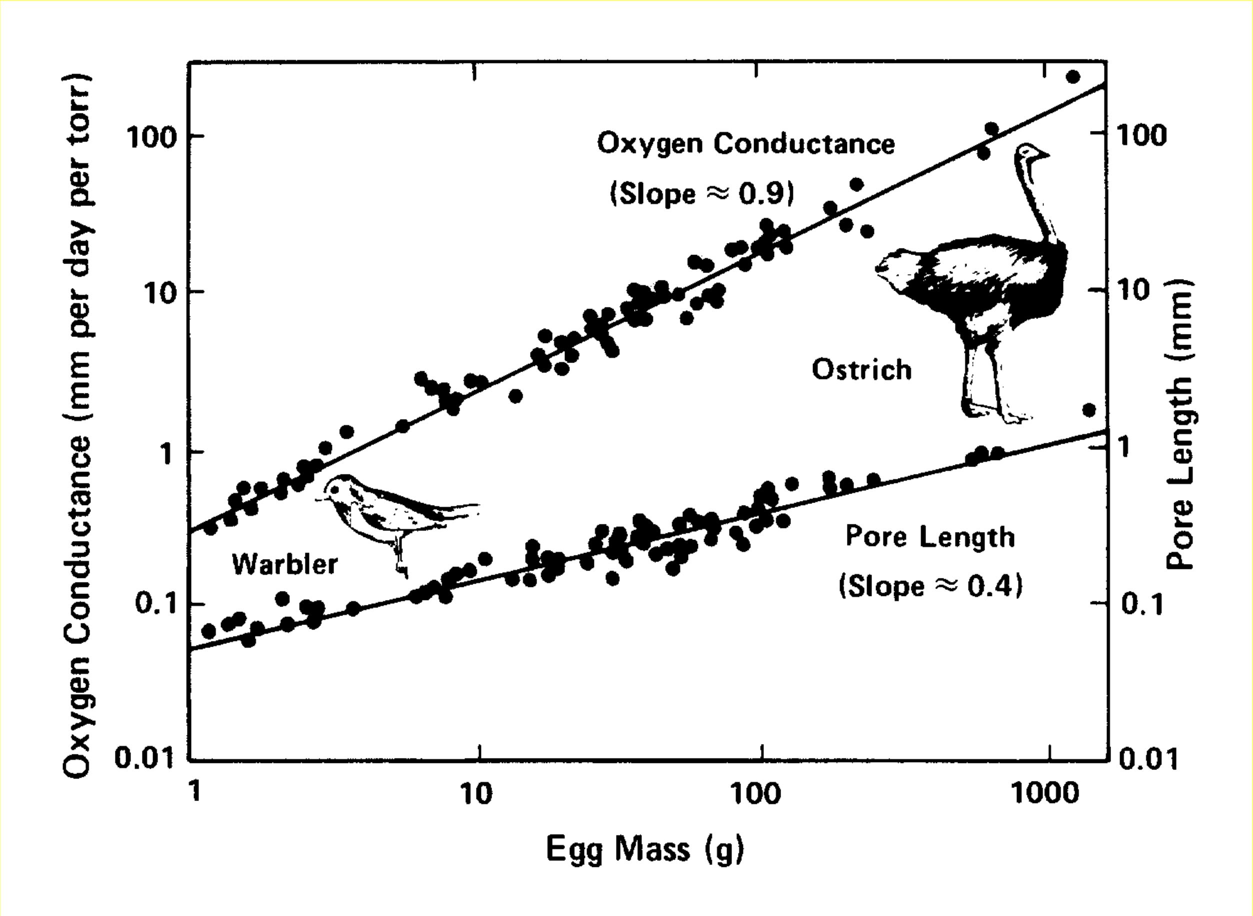
Note that best fit slope is ≈ 3/4
Something other than pure geometry is playing a role

Deviations from the geometrical or kinematic analysis reflects the dynamics of the system.

One can view deviations from naive scaling as a probe of the dynamics

Respiration

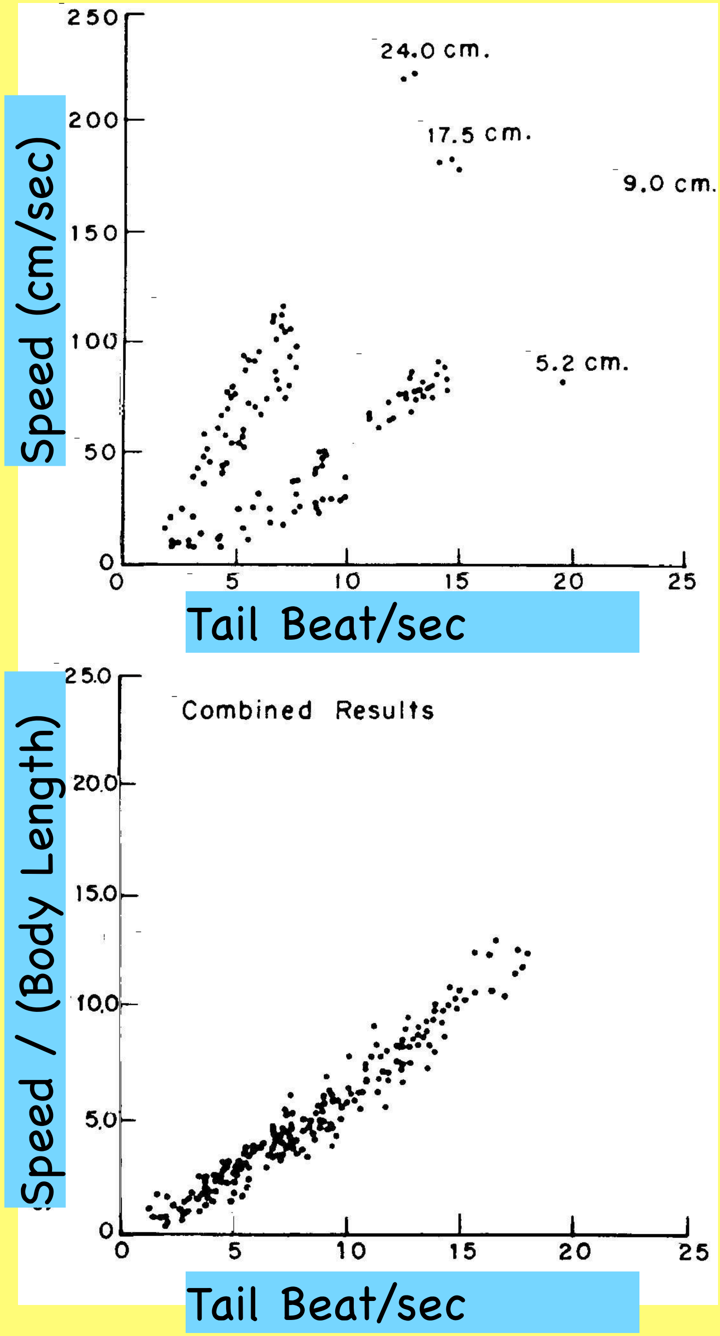
- Can we understand this?
- Pore length = thickness of shell suggests its strength = > $W^{1/3}$.
- Conductance $\propto$ total pore area and $\propto$ 1/pore length



Assume pore spacing the same from bird to bird, then the two factors go as Surface area ($W^{2/3}$) and 1/l ($1/W^{1/3}$)

$$K \propto \frac{W^{2/3}}{W^{1/3}} = W$$

Selecting the relevant variables



The Dace, a fresh water fish

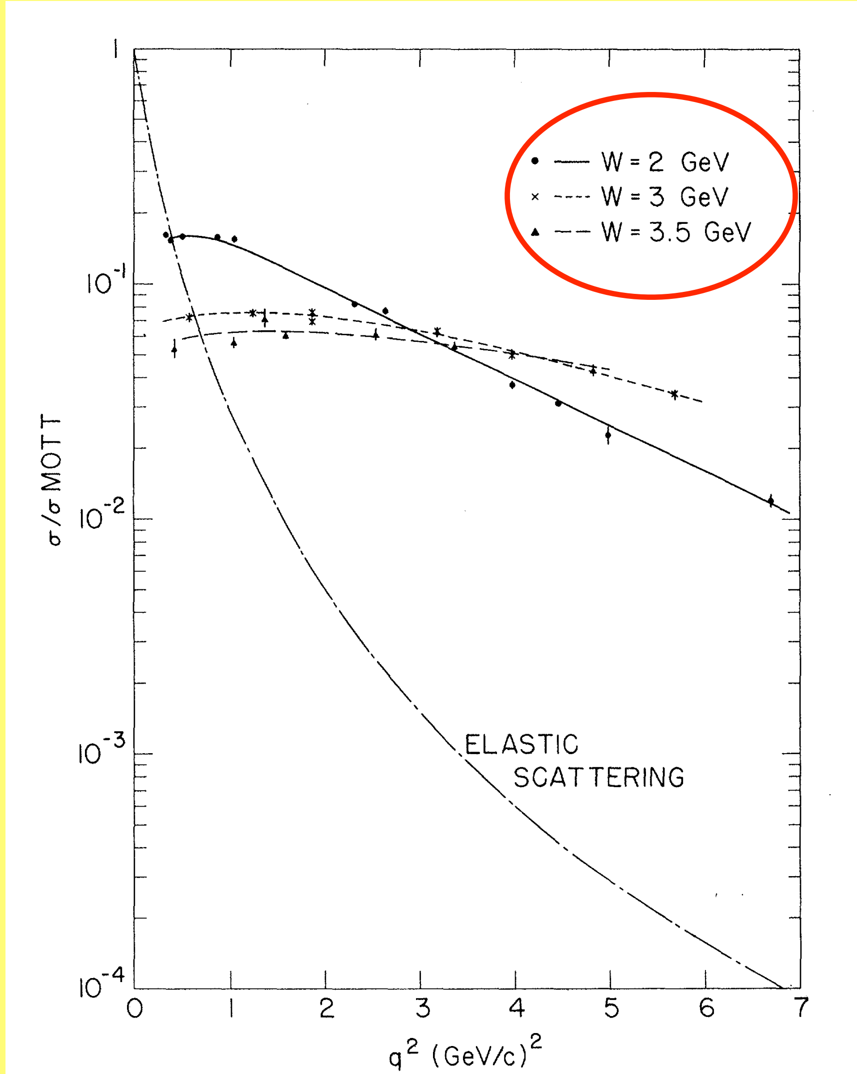
Scaling and scaling violations reveal information about the dynamics of the system

Knut Schmidt-Nielsen, from Scaling: Why is Animal Size So Important?

Scaling in DIS

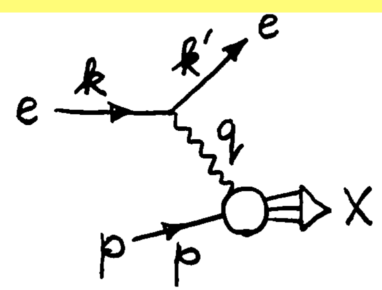
Existence of partons (quarks) revealed by DIS at SLAC in 1960's

Ratio of measured cross-section to pointlike prediction for the proton = form factor!



Invariant mass of the final hadronic state

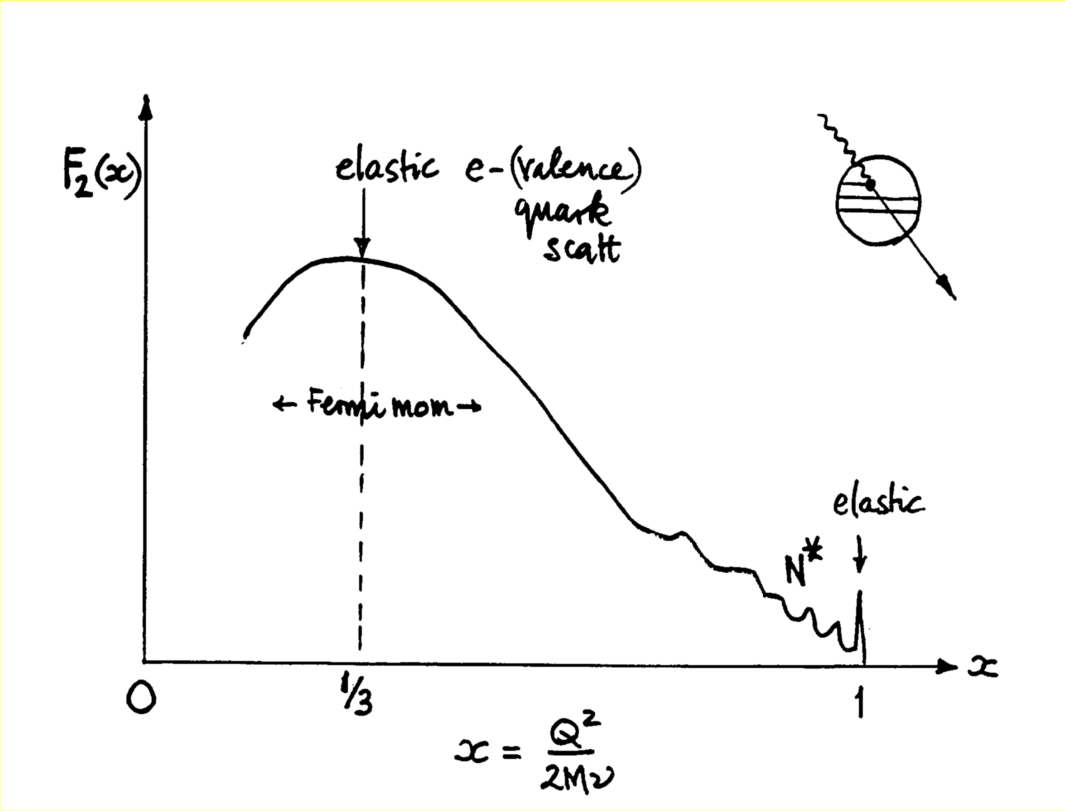
"Scaling" –in this regime,the form factors are approximately equal and are almost independent of momentum transfer...



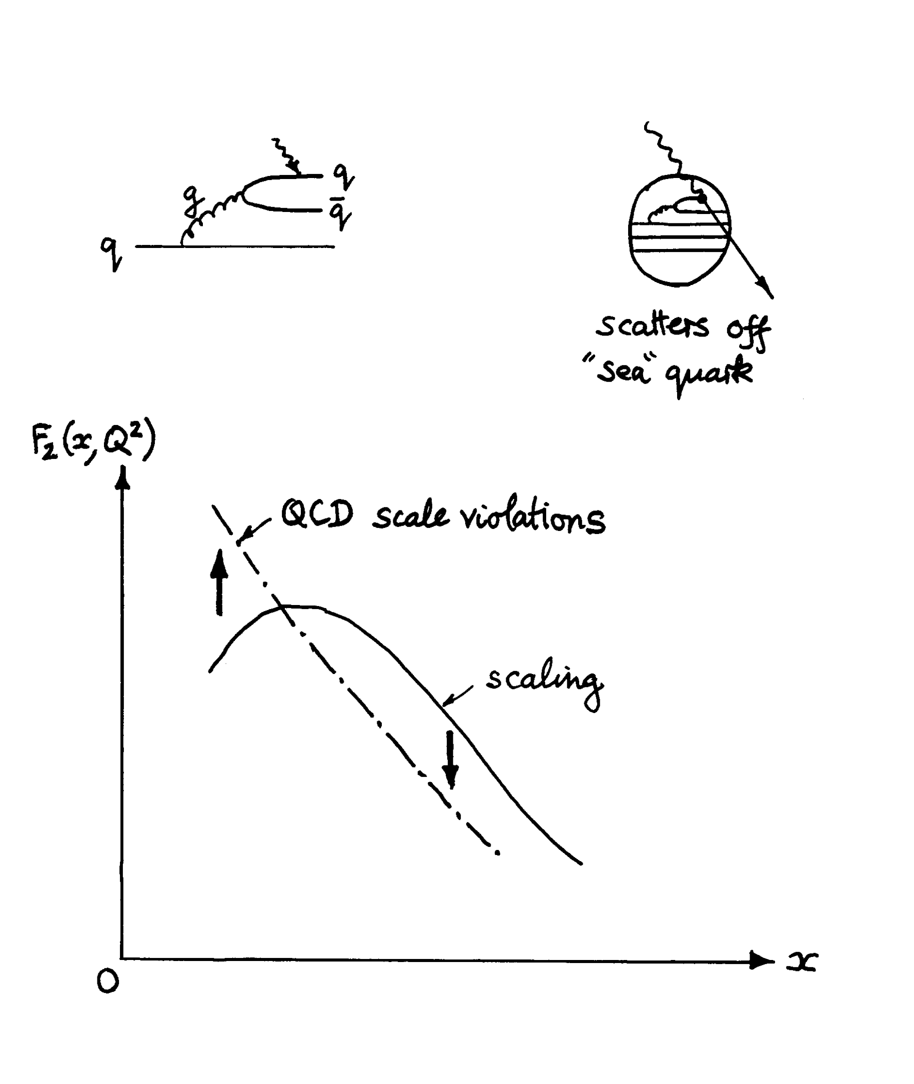
$Q^2 \equiv -q^2 \gg M^2$ "deep" $M \equiv M_p$

$W^2 = (p+q)^2 \gg M^2$ "inelastic"

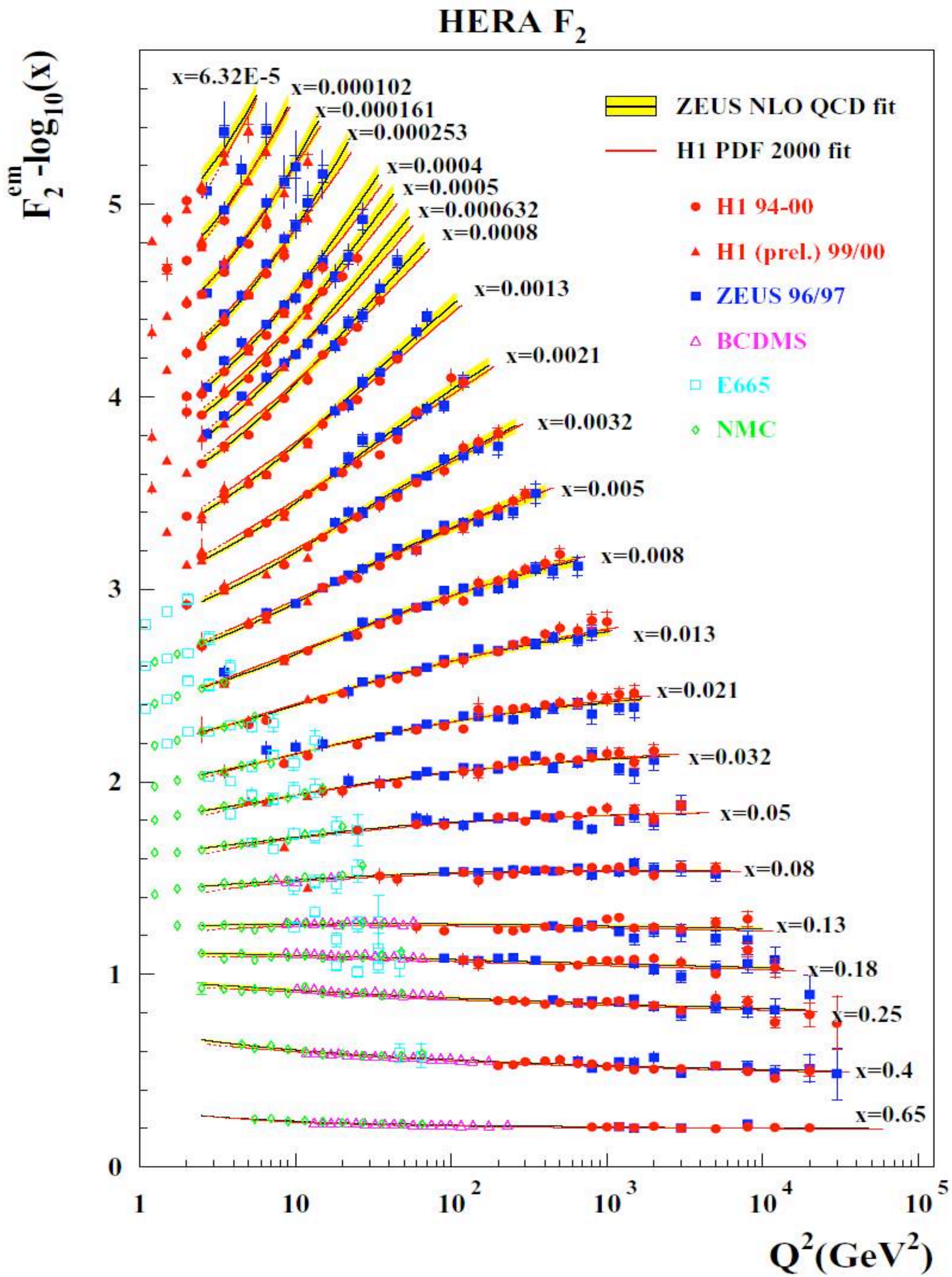
Quarks AND Gluons



Scaling



Scaling Violations



F_2 dominates cross-section

Range in x: 0.00001 – 1

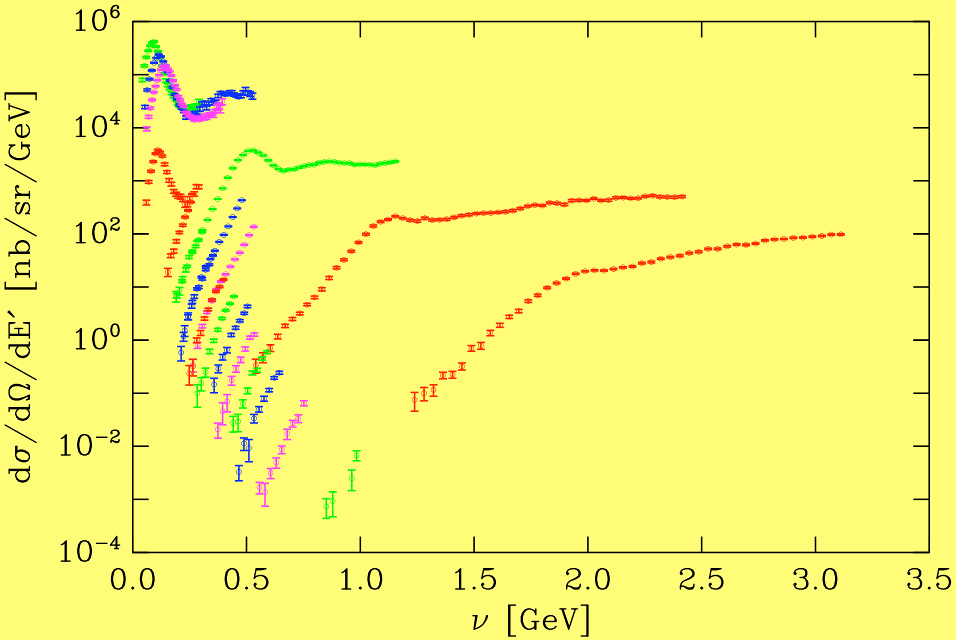
Range in Q^2 ~1 - 30000 GeV^2

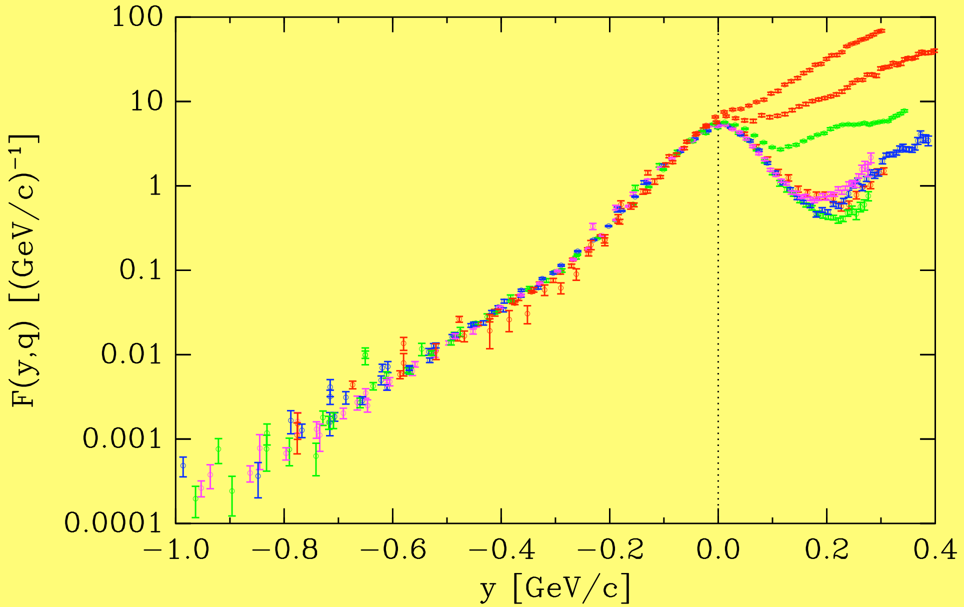
Measured with ~2-3% precision

Directly sensitive to sum of all quarks and anti-quarks

Indirectly sensitive to gluons via QCD radiation - scaling violations

y-scaling in inclusive electron scattering from ^{3}He





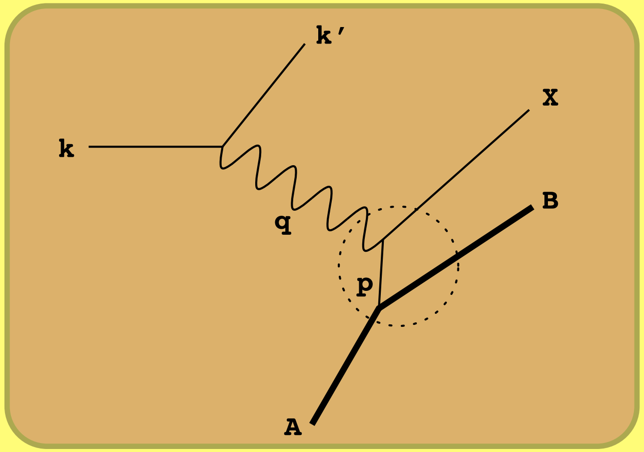
$$F(y) = \frac{\sigma^{\exp}}{(Z\tilde{\sigma}_p + N\tilde{\sigma}_n)} \cdot K$$

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

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

y-scaling in PWIA



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

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

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

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

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

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 $y= y(q,\omega)$
- 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

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

where

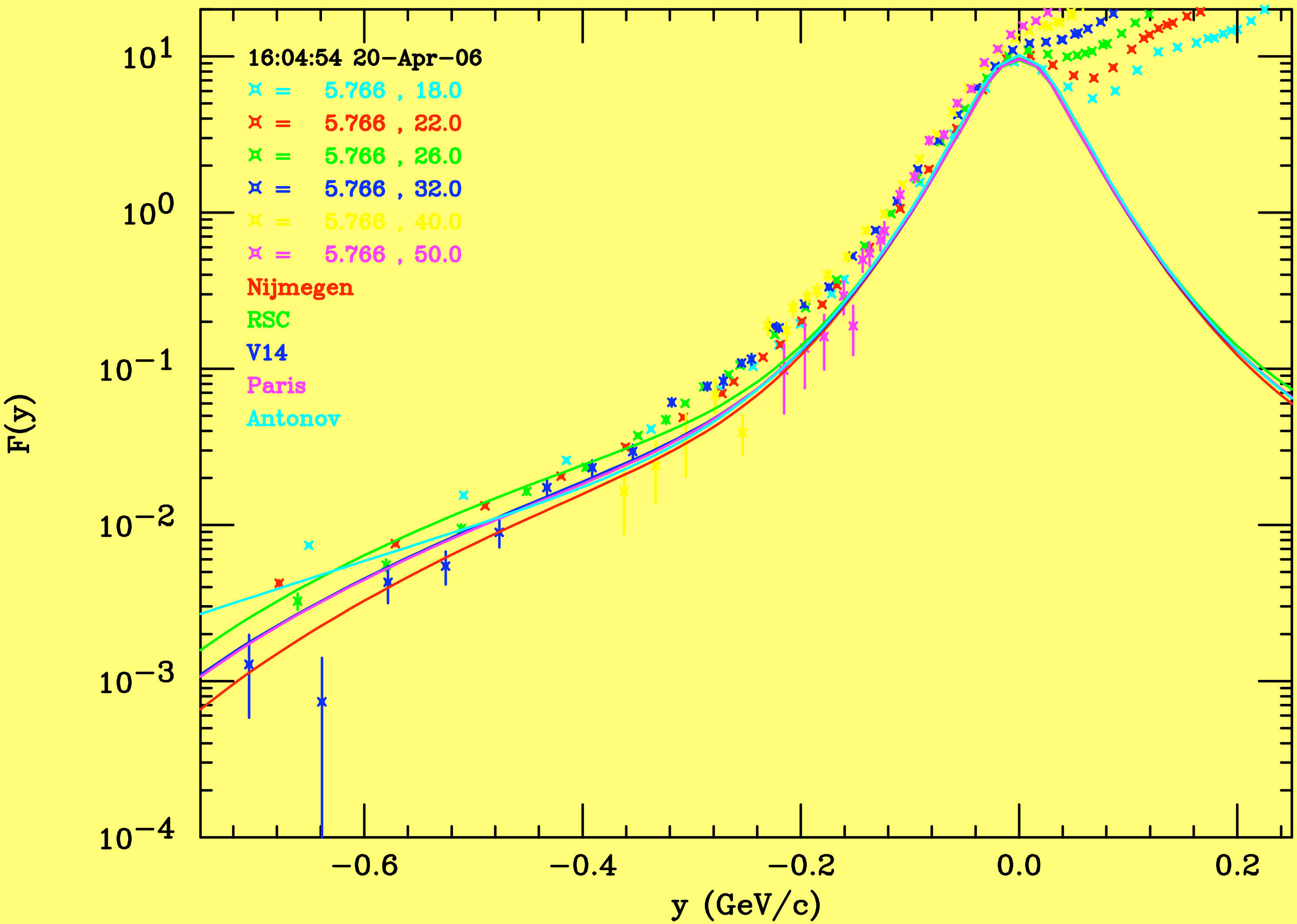
$$F(y) = 2\pi \int_{|y|}^{\infty} n(k) k dk$$

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

Assumptions & Potential Scale Breaking Mechanisms

- 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

y-scaling Deuteron (E-02-019)



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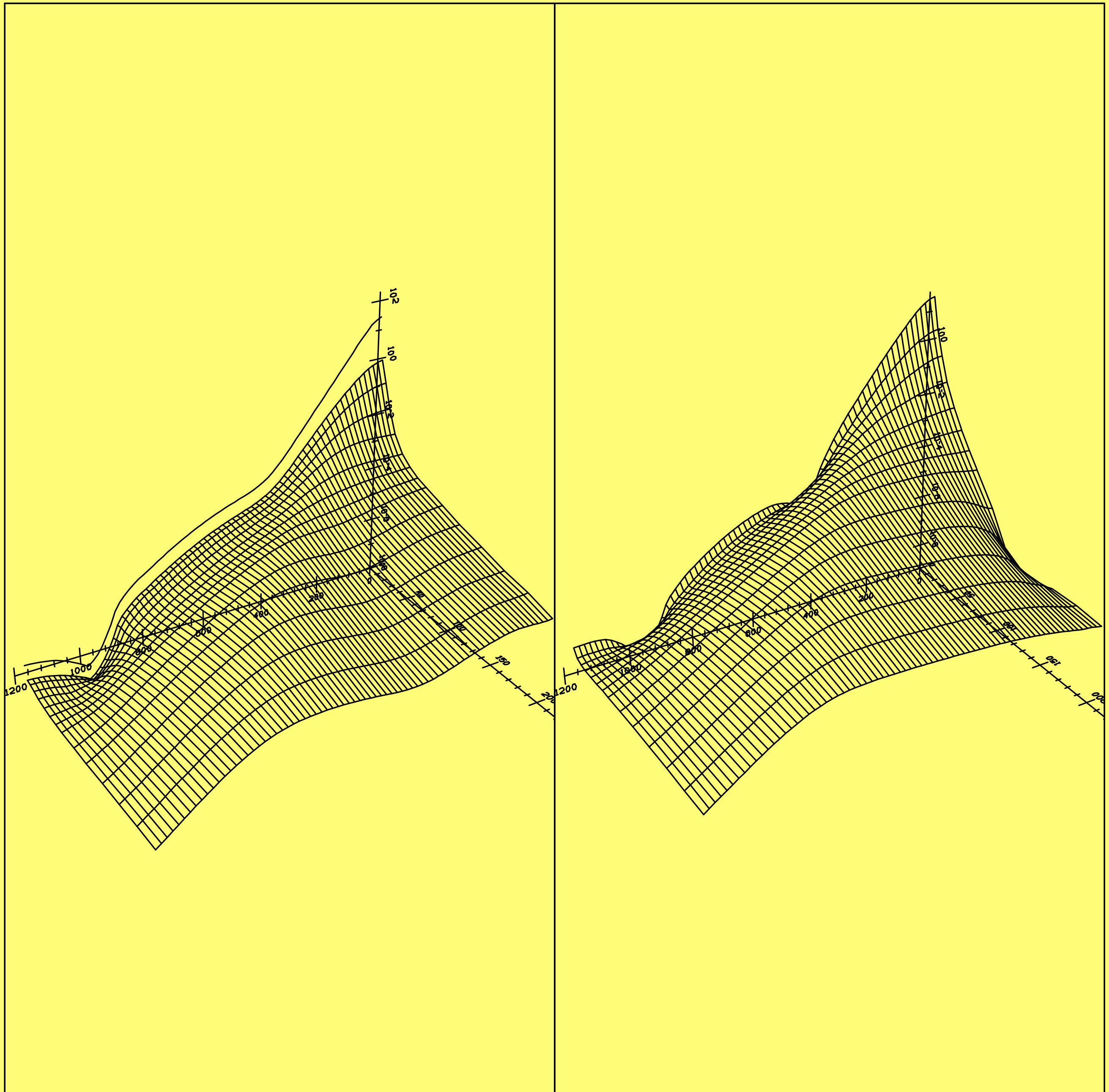
$$n(k) = -\frac{1}{2\pi y}\frac{dF(y)}{dy}$$

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

y ≈ -q/2 + mv/q

Helium-3

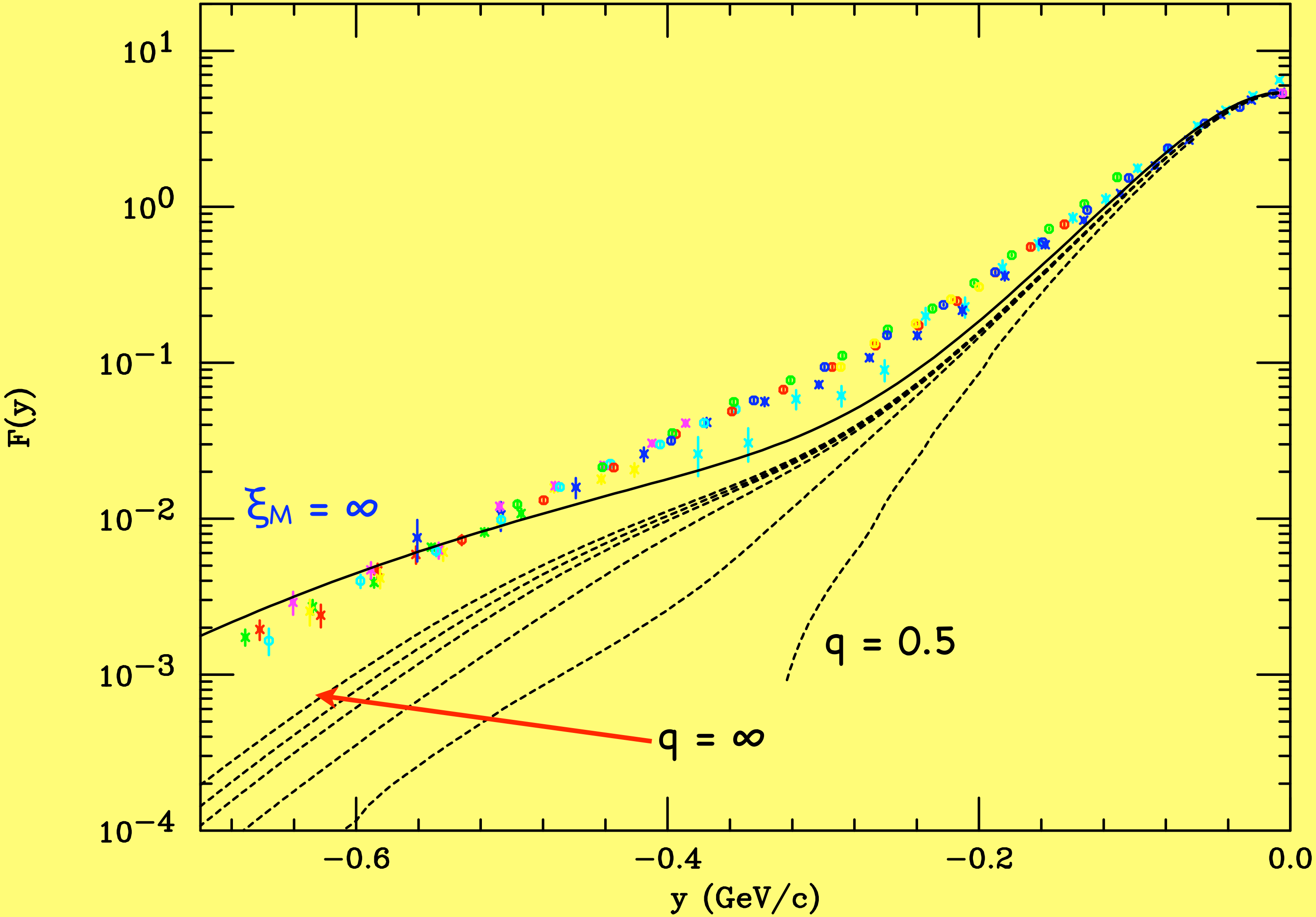


In nuclei the distribution of the strength in energy complicates the relationship between the scaling function and n(k).

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

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

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

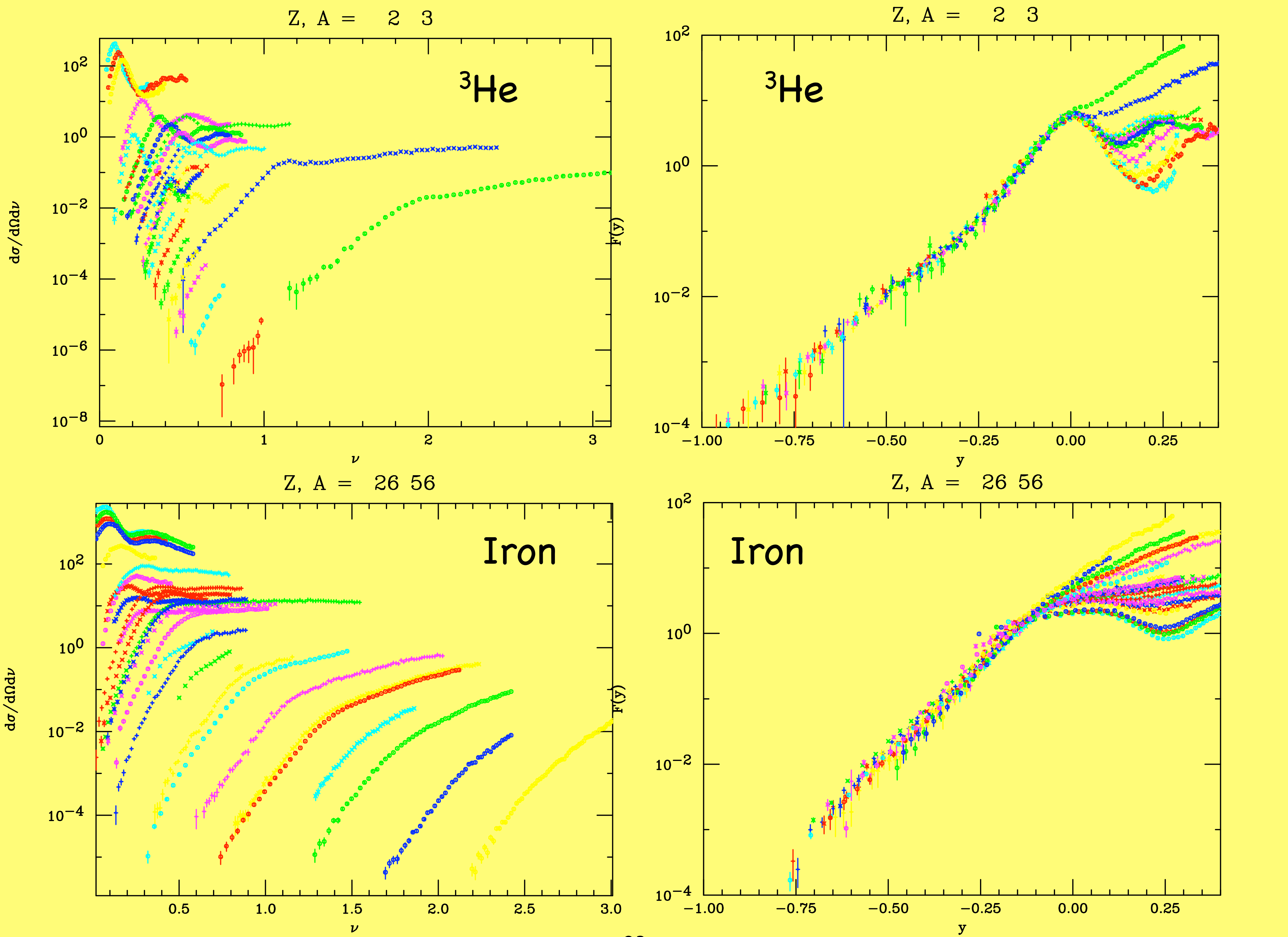


Is the energy distribution as calculated (scaling occurs at much lower q)?

Do other processes play a role?

FSI or/and DIS

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


Z, A = 2 3
³He
dσ/dΩdν
ν
Z, A = 2 3
³He
F(y)
y
Z, A = 26 56
Iron
dσ/dΩdν
ν
Z, A = 26 56
Iron
F(y)
y

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.

PHYSICAL REVIEW B VOLUME 30, NUMBER 1

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

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Atomic Energy of Canada Limited, Chalk River, Ontario, Canada K0J 1J0
(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.

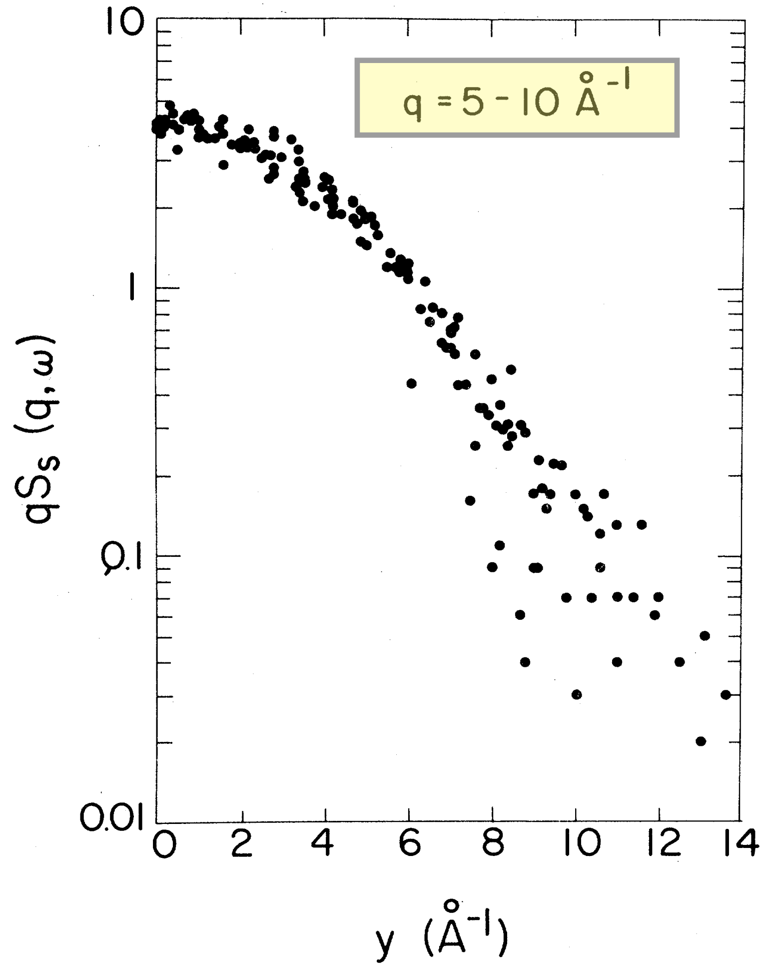


FIG. 1. y scaling in liquid neon. $qS_s(q,\omega)$ is shown in arbitrary units as a function of $y=(m/\hbar q)(\omega-\omega_r)$ for liquid neon at $T=26.9$ K for the eleven values of q in the range 5.0—10.0 Å^{-1}, which were used in the determination of the momentum distribution in Ref. 7. The data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

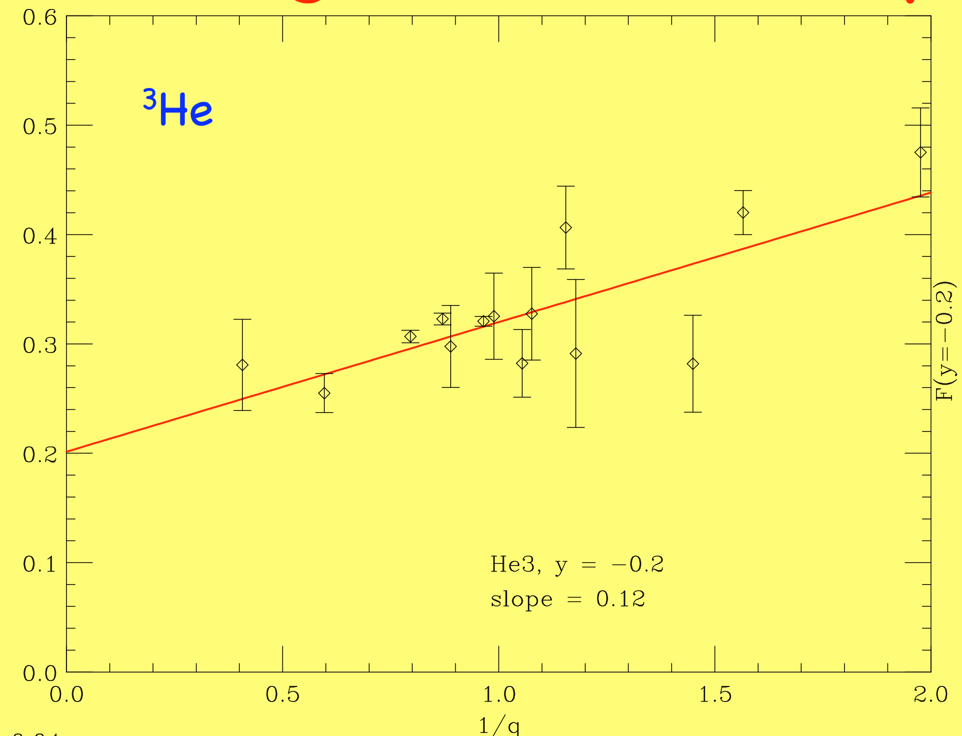
Momentum distributions are "distorted" by the presence of FSI

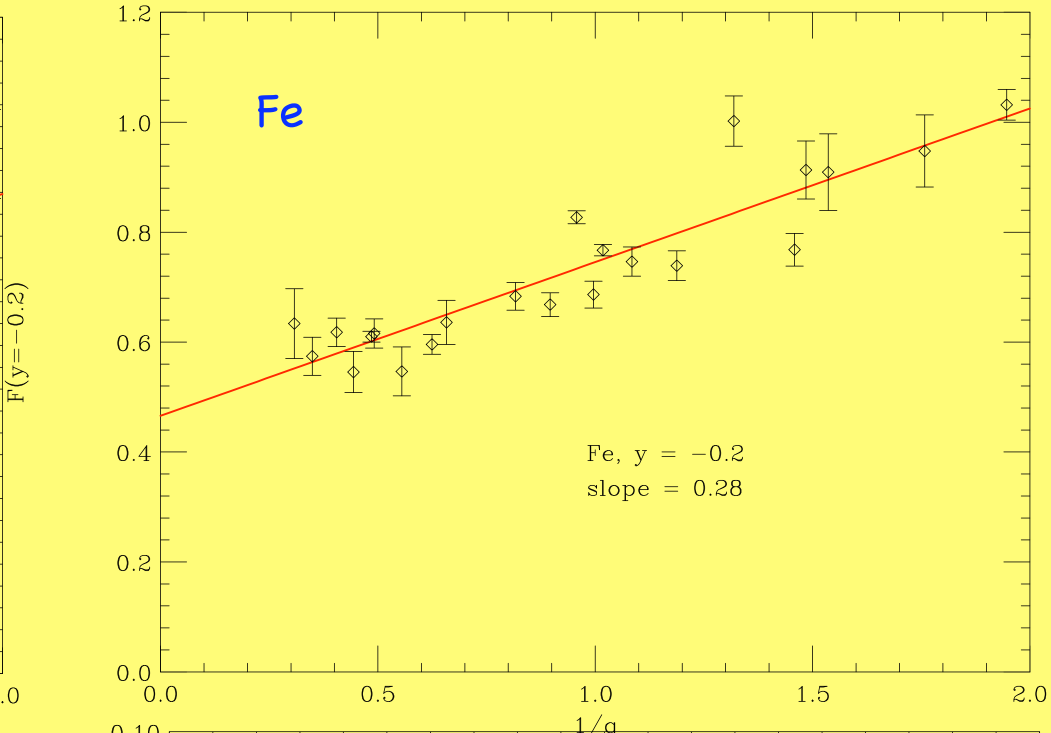
y-scaling as a test for presence of FSI

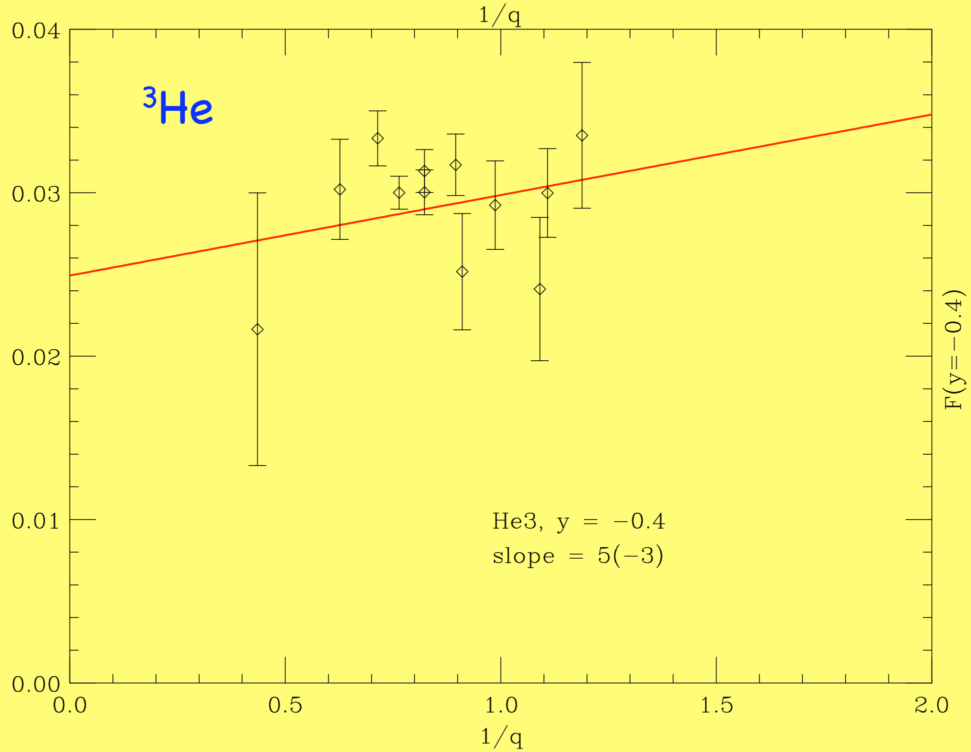
FSI have a 1/q dependence

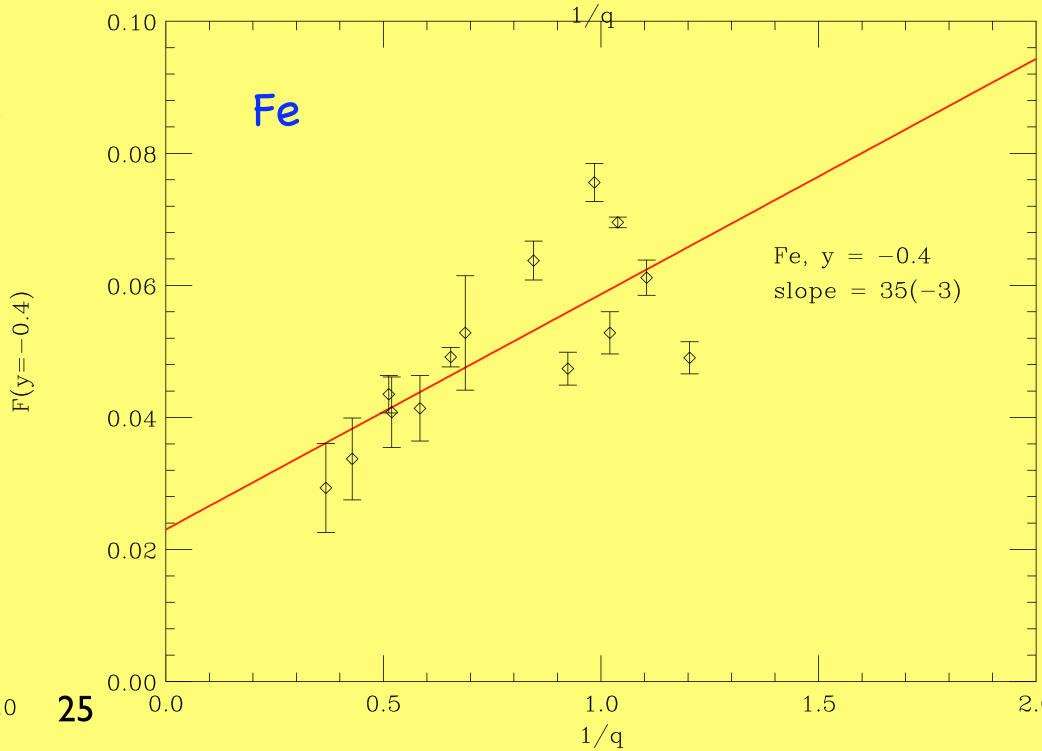
Weinstein & Negele PRL 49 1016 (1982)

Convergence of F(y,q)



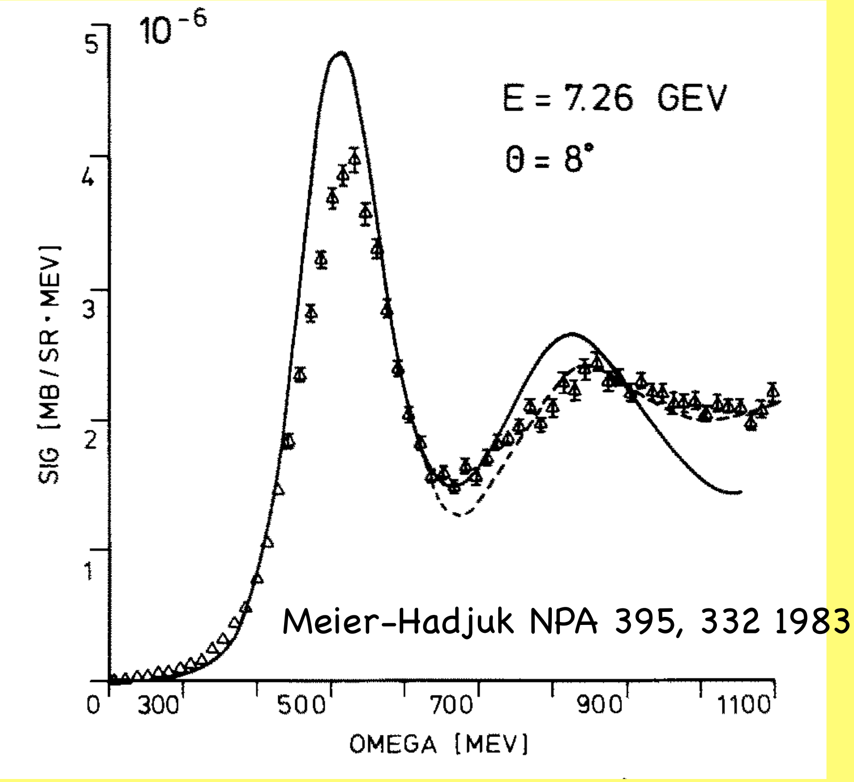


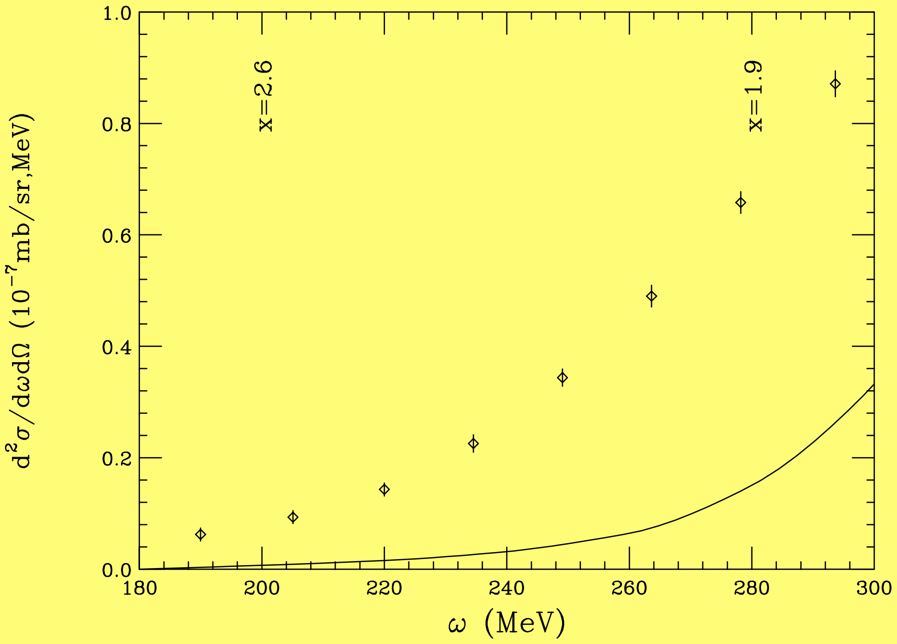




In (e,e′p) flux of outgoing protons strongly suppressed: 20-40% in C, 50-70% in Au

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

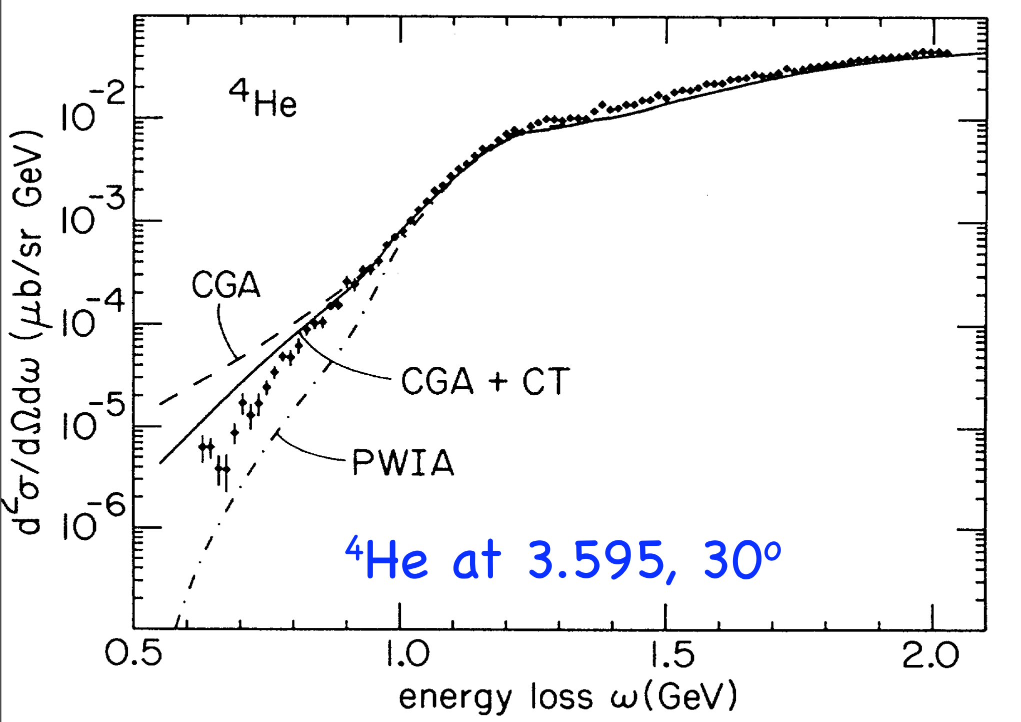




FSI has two effects: energy shift and a redistribution of strength

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

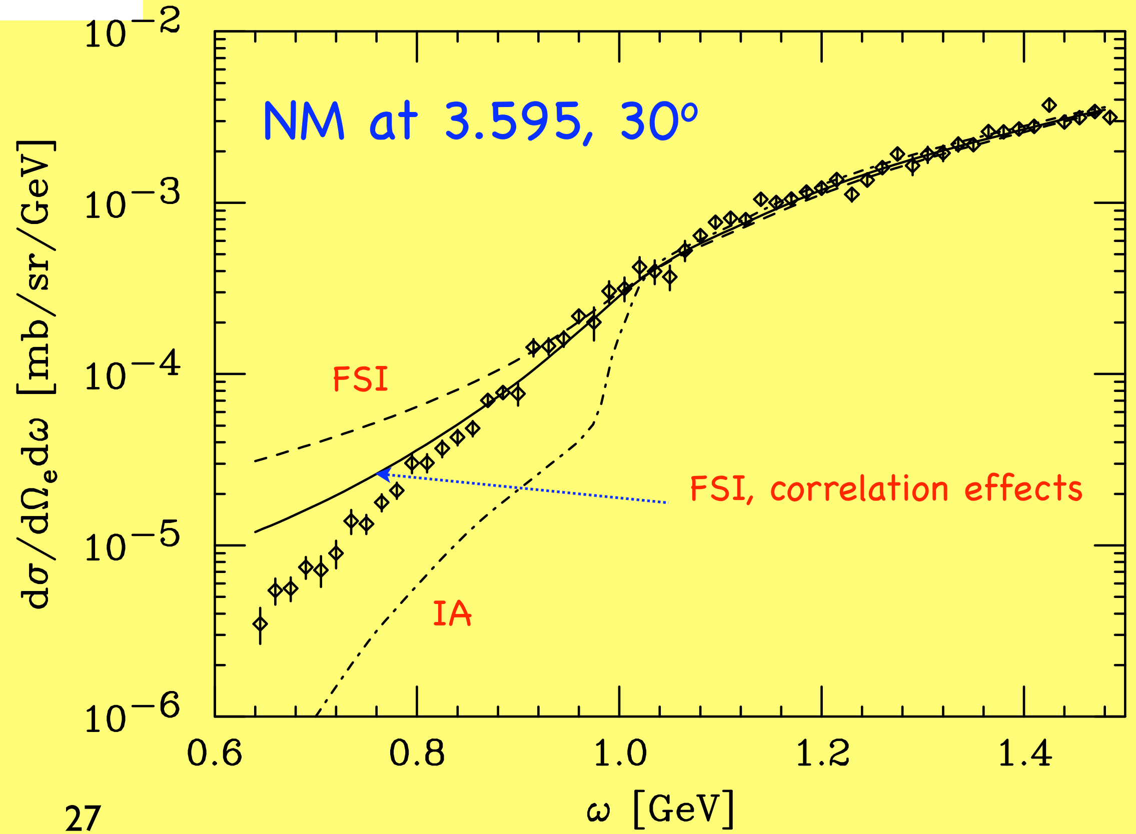
Final State Interactions in CGA



Benhar et al. PRC 44, 2328

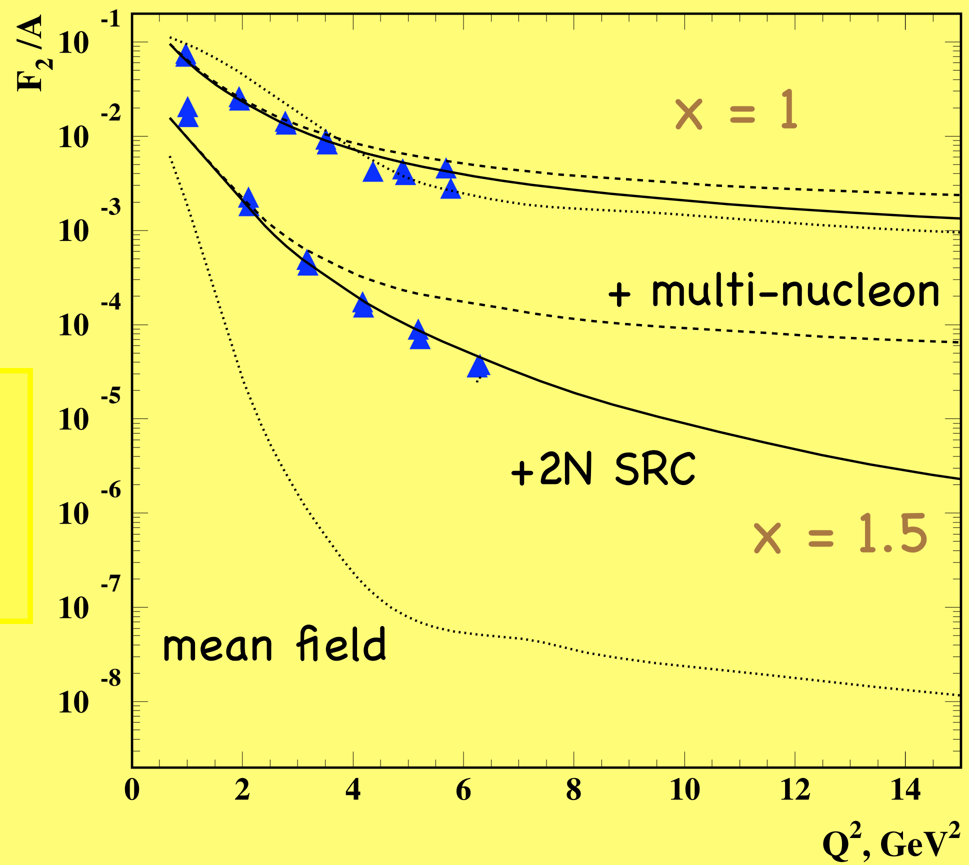
Benhar, Pandharipande, PRC 47, 2218

Benhar et al. PLB 3443, 47



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.

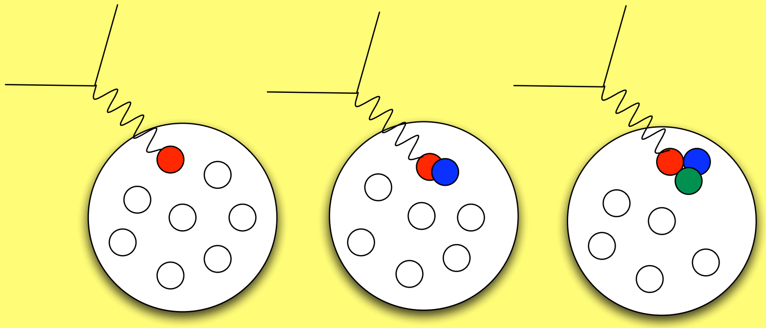
11 GeV can reach Q^2= 20(13) GeV^2 at x = 1.3(1.5)

- very sensitive, especially at higher x values

CS Ratios and SRC

In the region where correlations should dominate, large x,

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



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

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

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

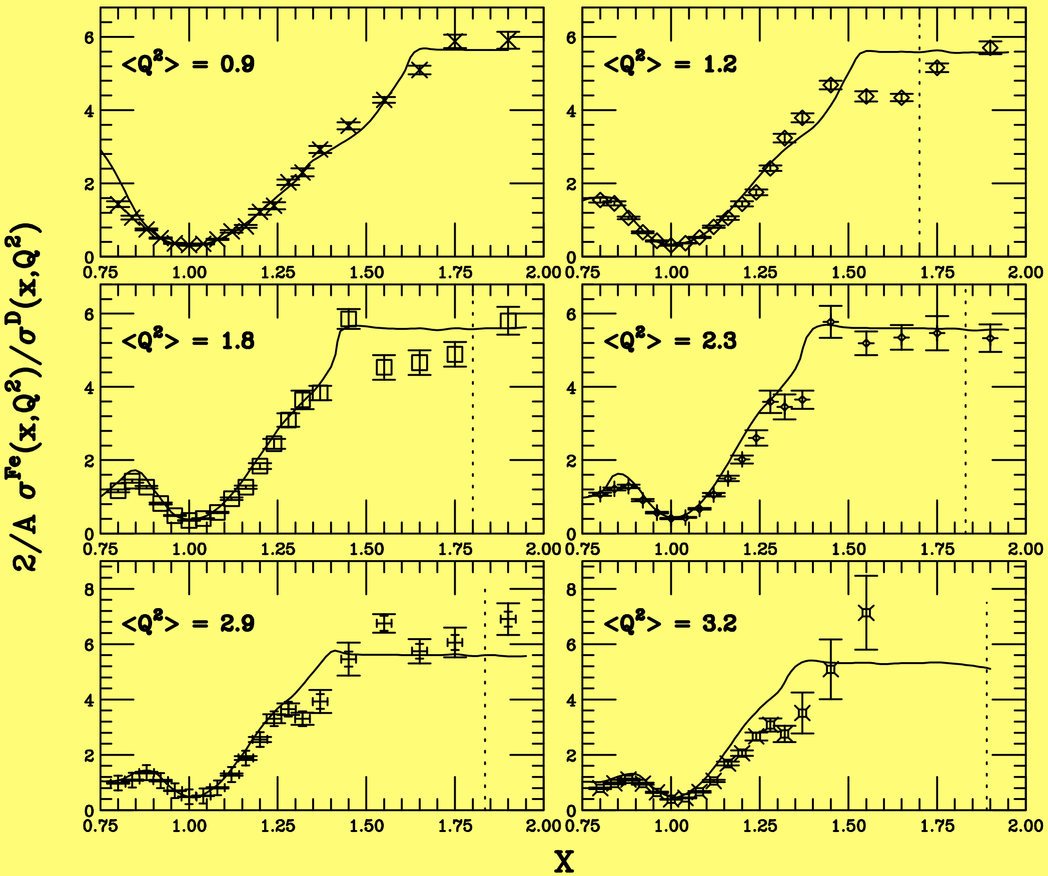
$$\frac{3}{A}\frac{\sigma_A(x,Q^2)}{\sigma_{A=3}(x,Q^2)} = a_3(A)\Big|_{2<x\leq 3}$$

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

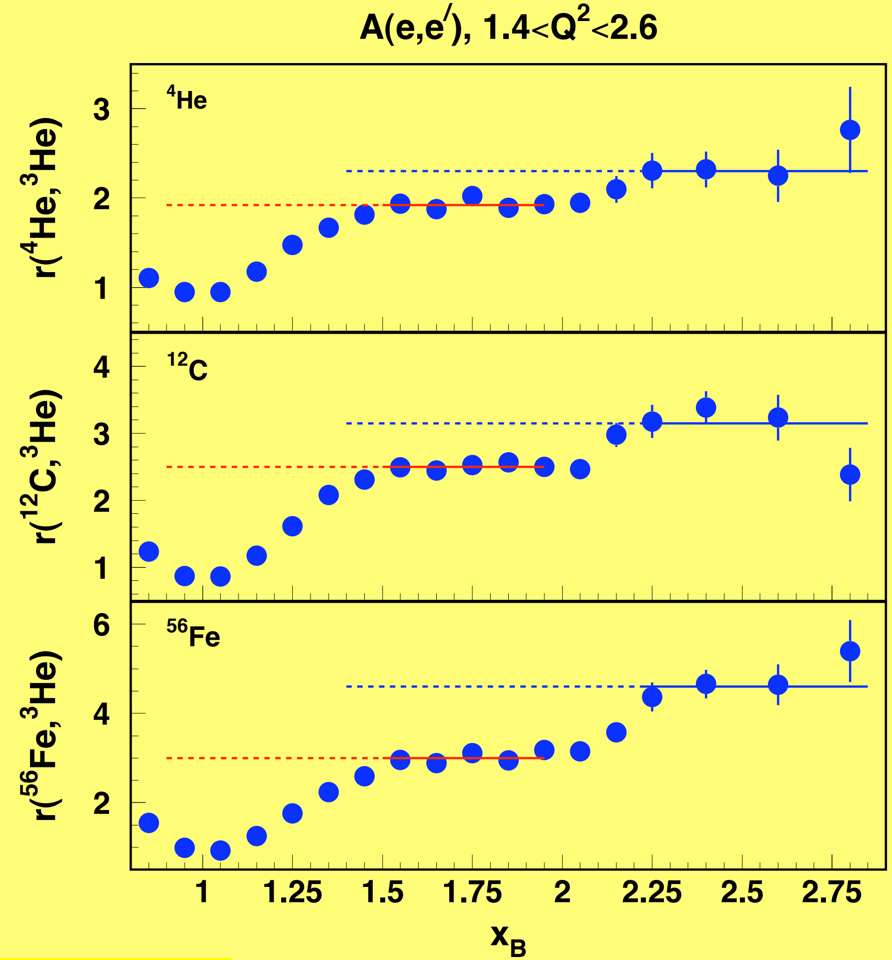
$a_j(A)$ is proportional to probability of finding a j-nucleon correlation

Ratios and SRC

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



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



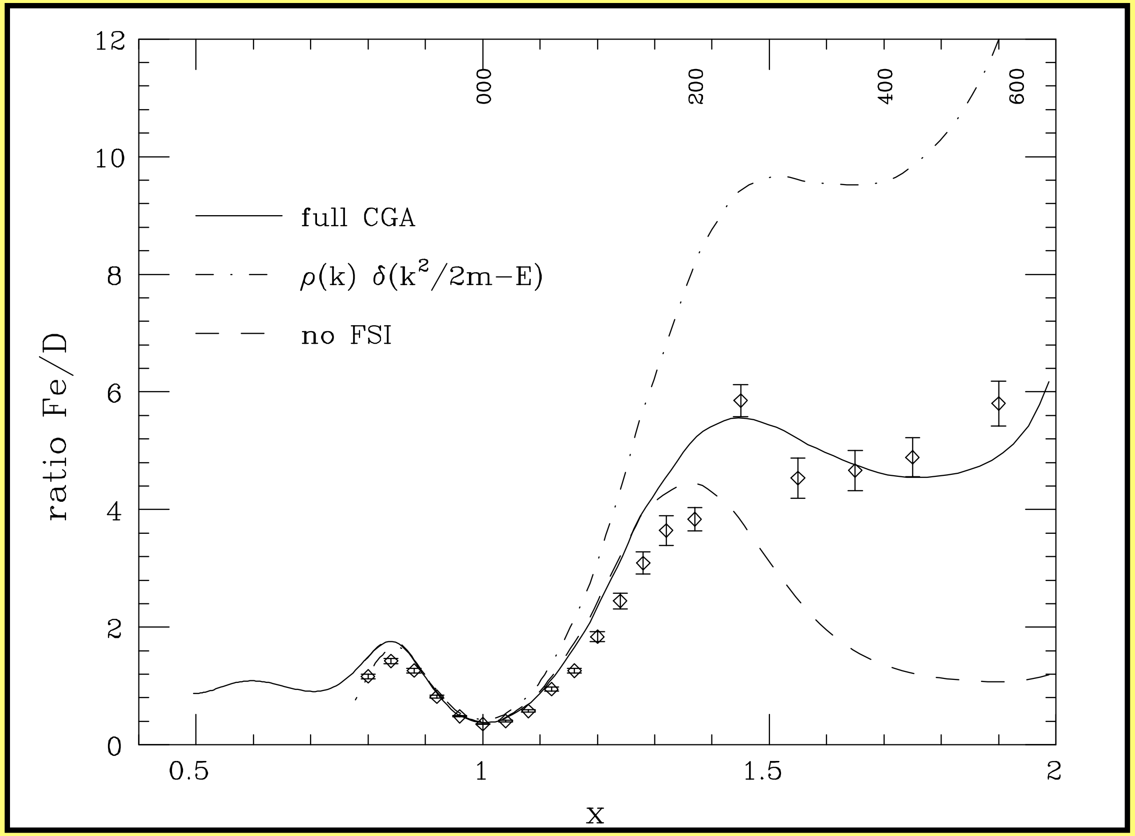
$a_j(A)$ is proportional to probability of finding a j-nucleon correlation

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

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

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

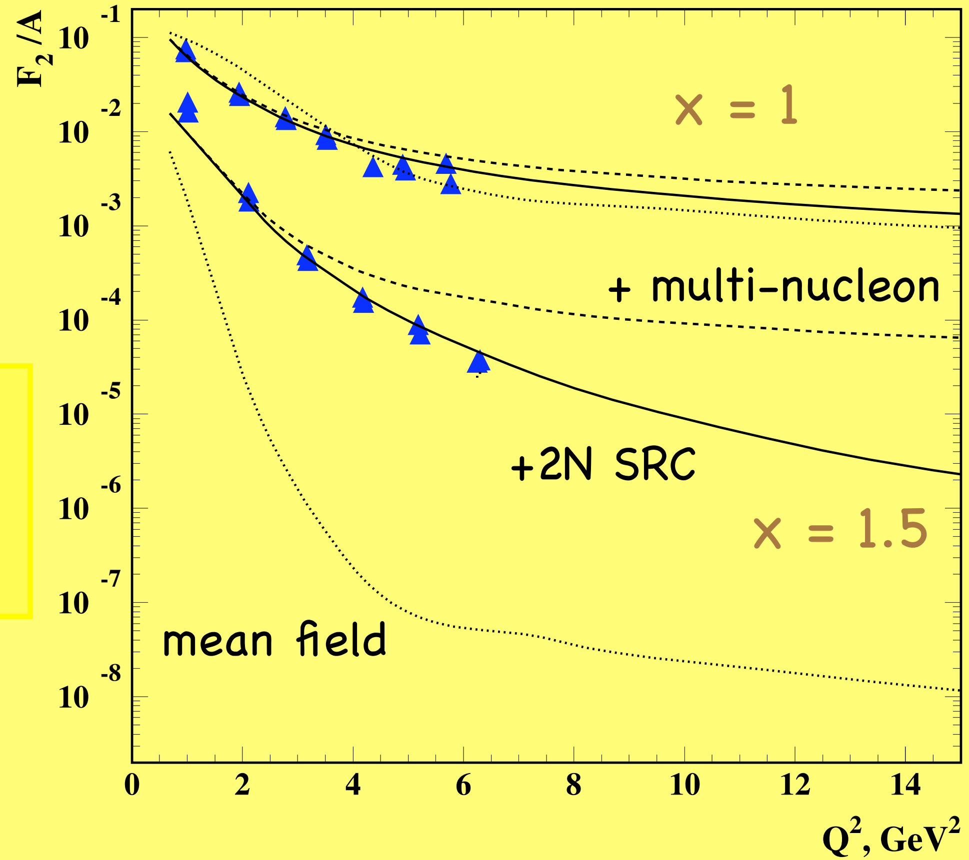
The solution

- Direct ratios to ^2H, ^3He, ^4He 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

Sensitivity to SRC increase with Q^2 and x

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

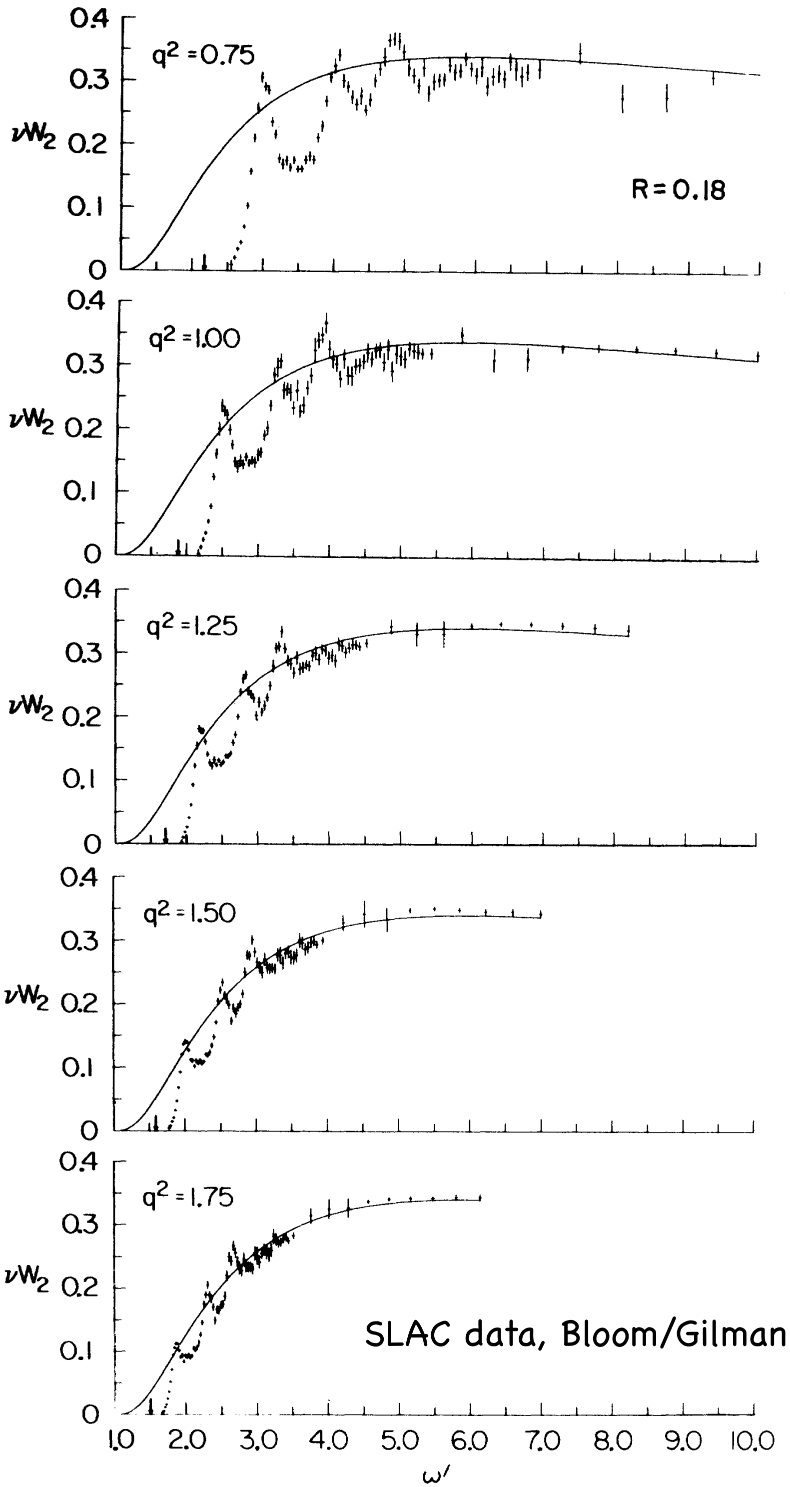
Dotted = mean field approx.
Solid = +2N SRCs.
Dashed = +multi-nucleon.



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

- very sensitive, especially at higher x values

Duality= resonances average to DIS



SLAC data, Bloom/Gilman

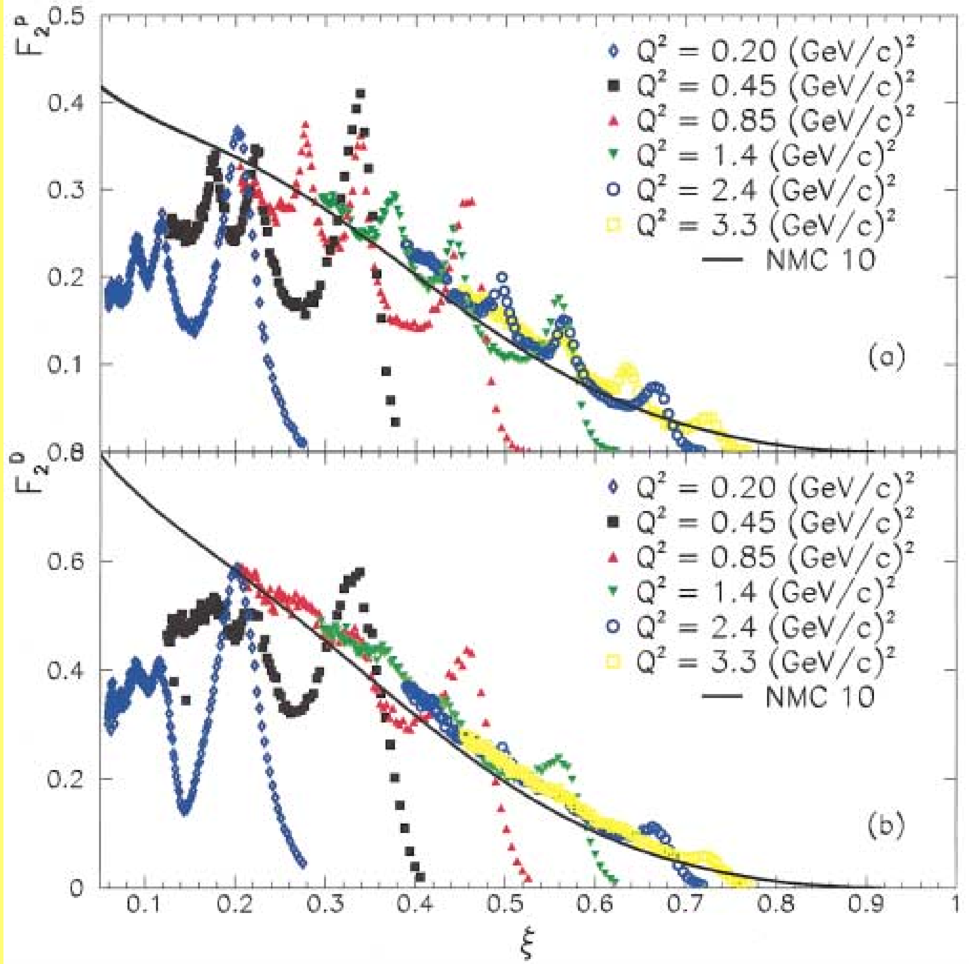
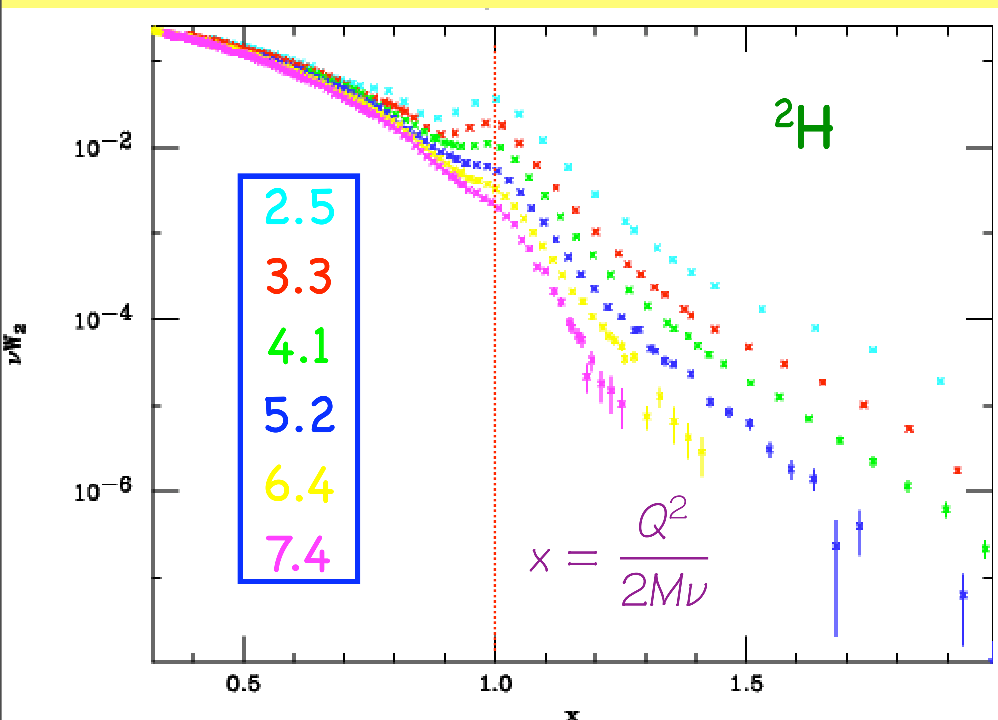


FIG. 1 (color). Extracted F_2 data in the nucleon resonance region for hydrogen (a) and deuterium (b) targets, as functions of the Nachtmann scaling variable ξ. For clarity, only a selection of the data is shown here. The solid curves indicate the result of the NMC fit to deep inelastic data for a fixed $Q^2 = 10\ (\mathrm{GeV}/c)^2$ [16].

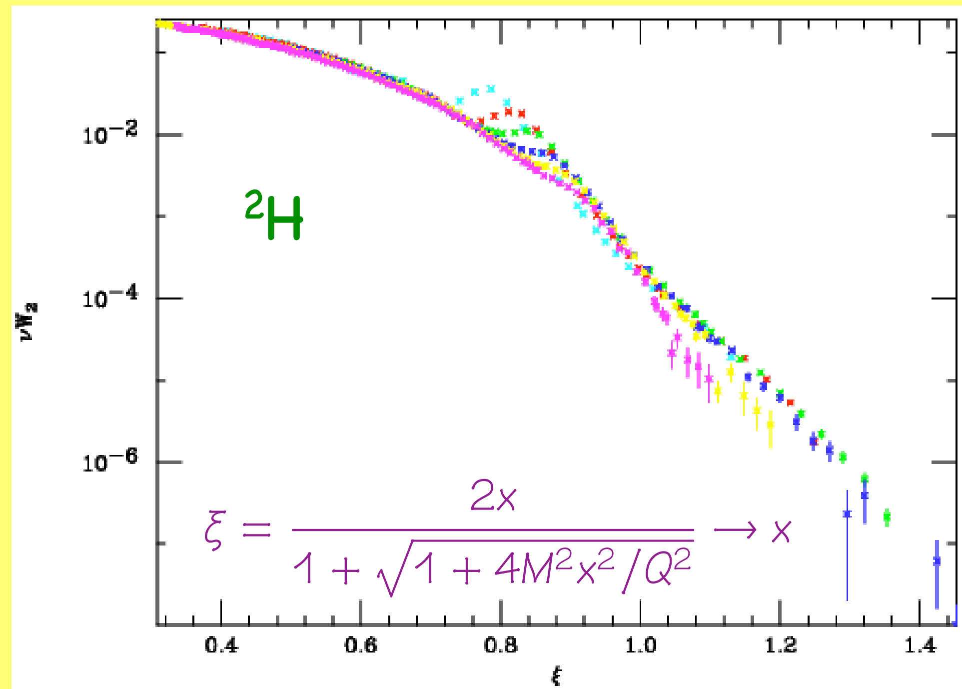
JLAB data, Niculescu et al.

x and ξ scaling

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

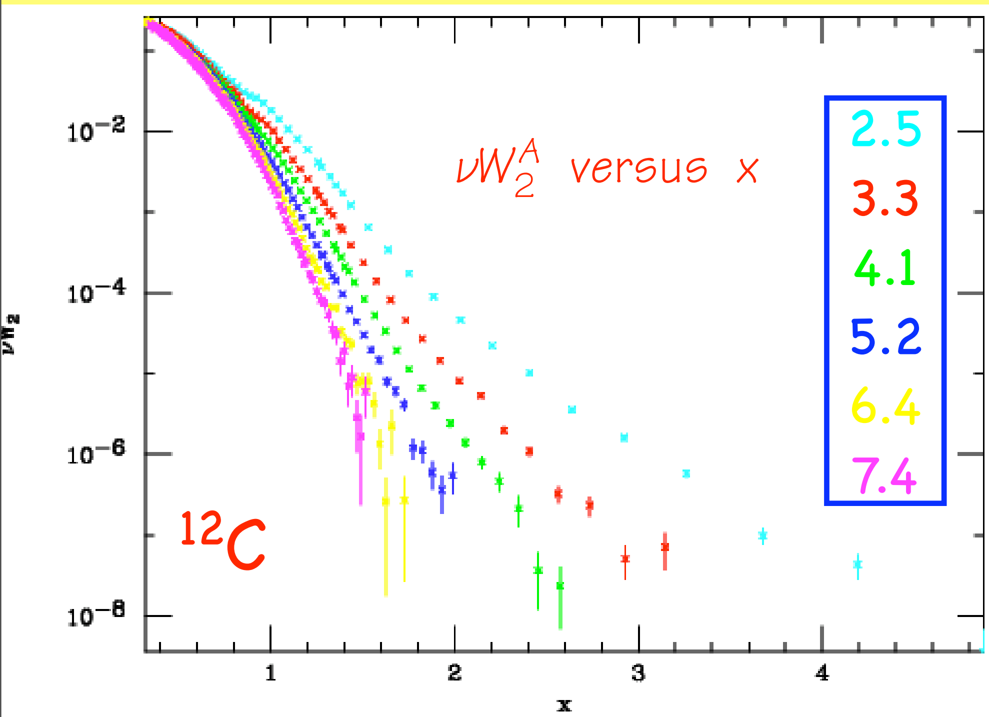


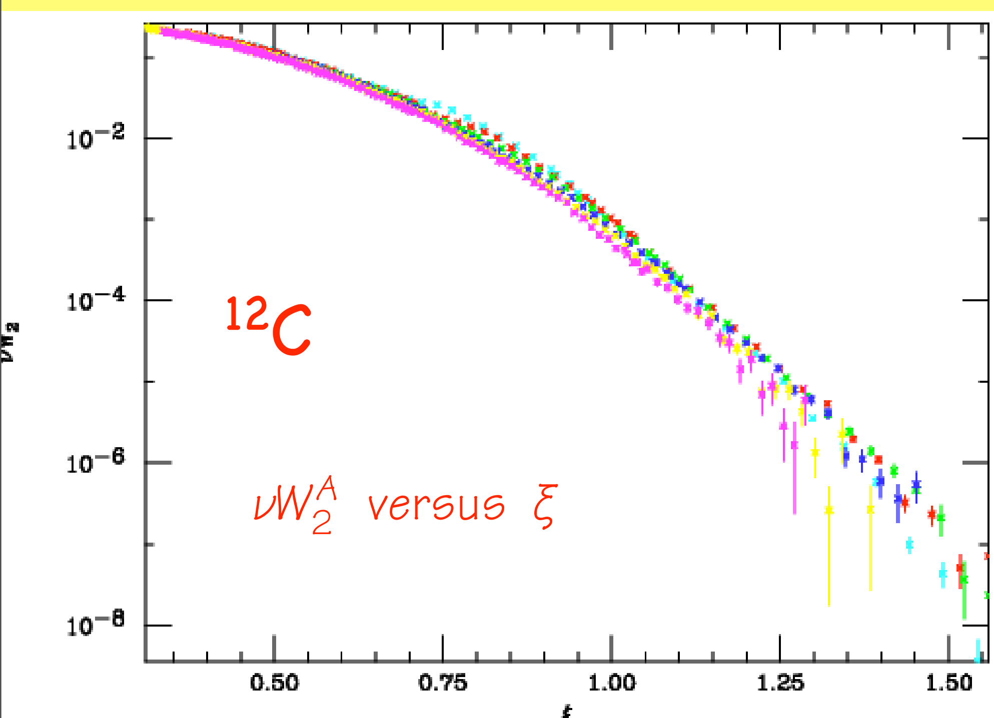
νW_2^A versus x



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.

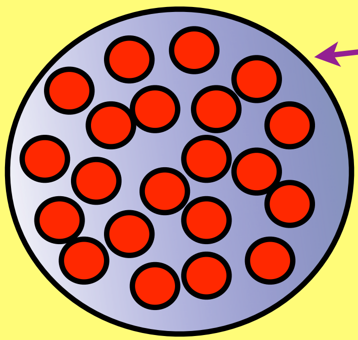
Local duality (averaging over finite range in x) should also be valid for elastic peak at x = 1 if analyzed in ξ

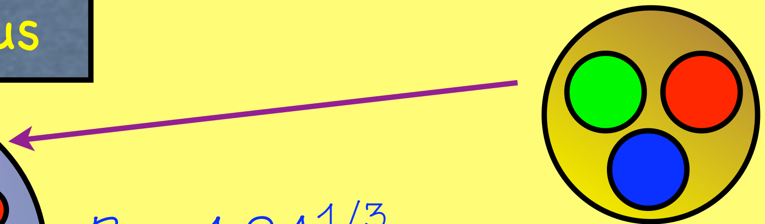
$$F_2^A(\xi) = \underbrace{\int_\xi^A dz F(z) F_2^n(\xi/z)}_{\text{averaging}}$$

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

Medium Modifications generated by high density configurations

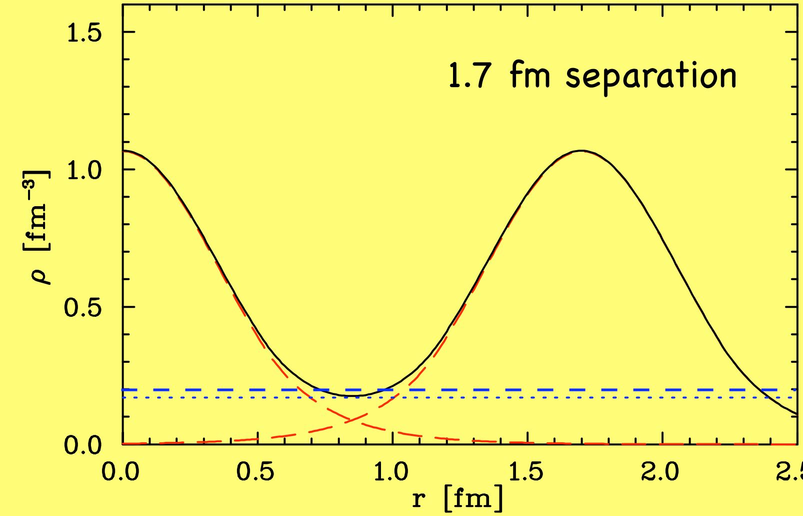
Gold nucleus





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

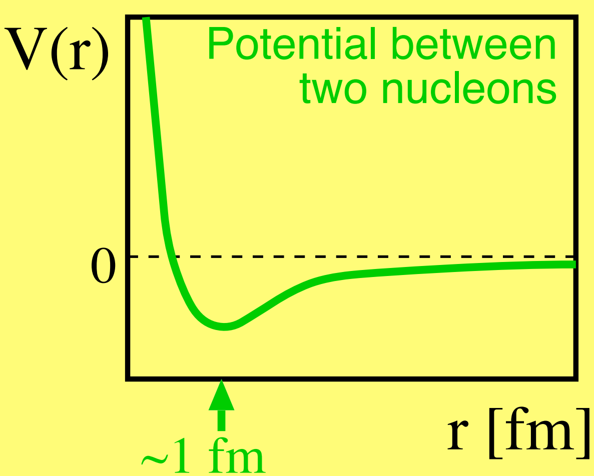
$Volume = \frac{4}{3}\pi R^3 \simeq 1400 fm^3$



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

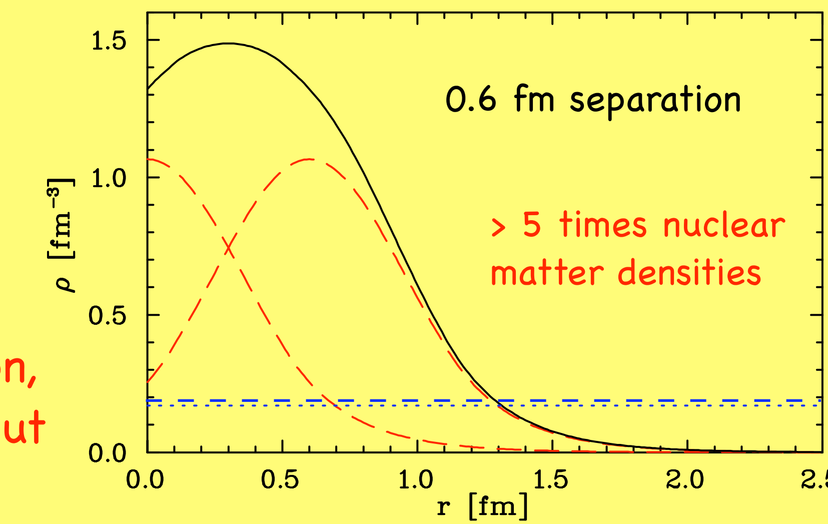
197 times 4.2 fm^3 ≈ 830 fm^3

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

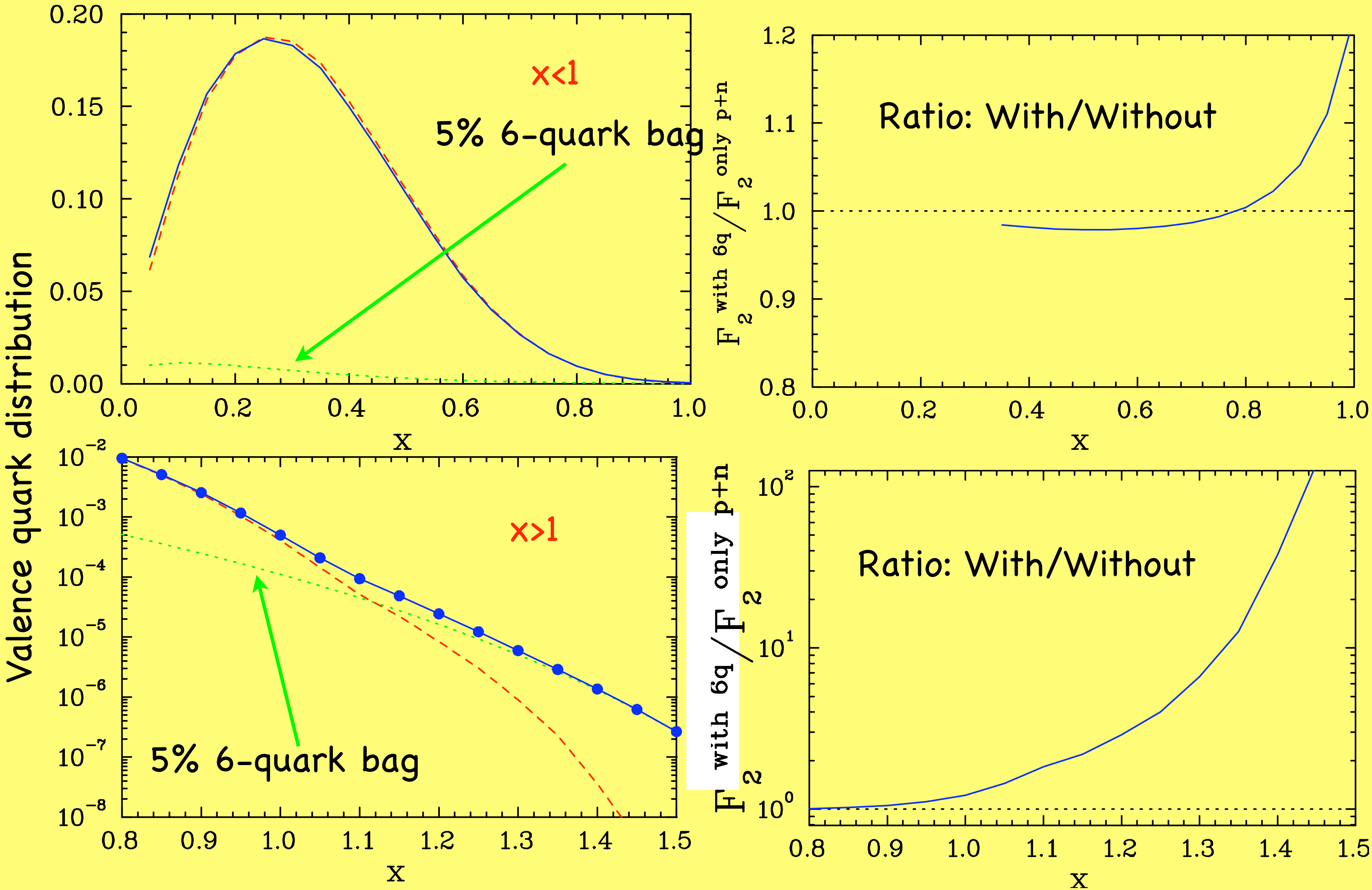


Comparable to neutron star densities!

High enough to modify nucleon structure?

To which nucleon does the quark belong?

Sensitivity to non-hadronic components



Mulders & Thomas

Quark distributions at x > 1

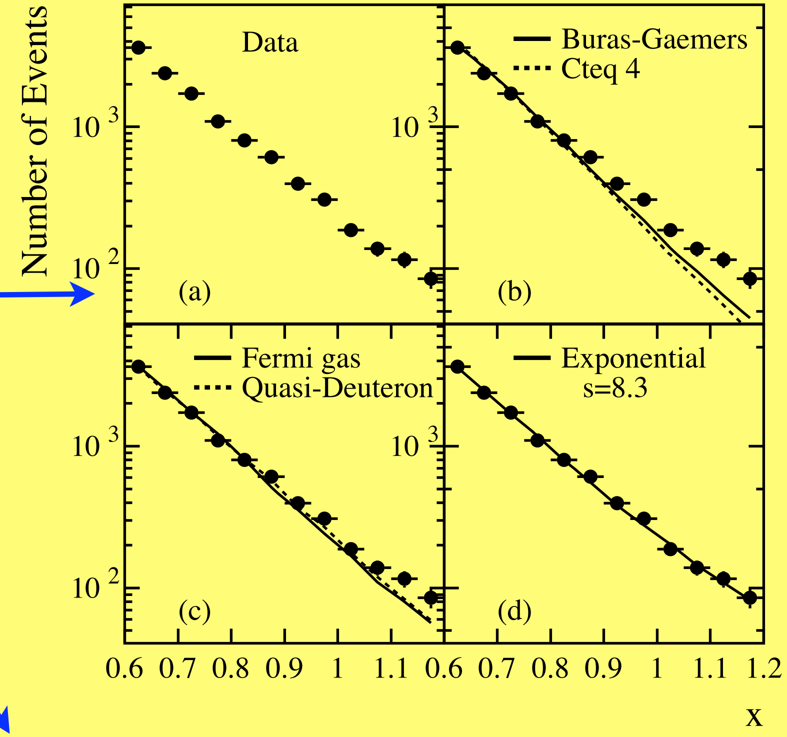
Two measurements (very high Q^2) exist so far:

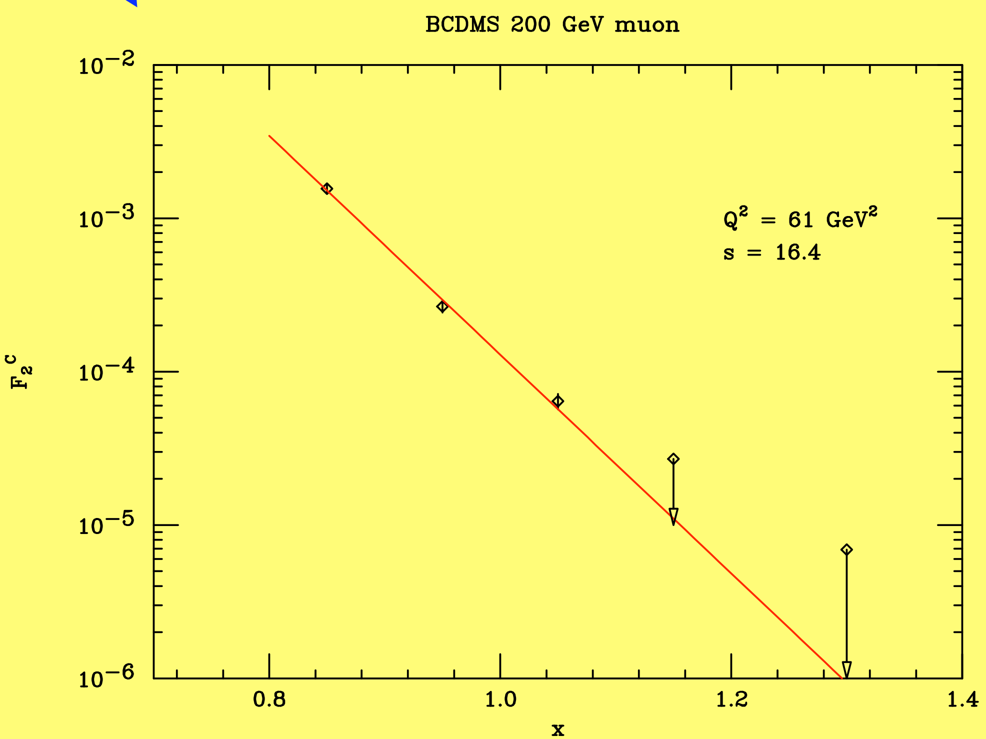
CCFR (ν–C): $F_2(x) \propto e^{-sx}$ s = 8

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

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

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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.