Inclusive scattering from nuclei: EMC effect, Short range correlations, superfast quarks, and a little duality

John Arrington
Argonne National Lab

Inclusive scattering at ***large x***:
Nuclear structure functions, EMC effect, duality

- SLAC-E139 (EMC effect)
- JLab E03-103 (EMC effect, Duality, F_2 for A=2,3,4)
- JLab E99-118/E00-116/E02-109/E04-001
  (Duality, F_1 & F_2 for H, D, A)

Inclusive scattering at ***really large x*** (x>1):
High momentum nucleons, short range correlations

- SLAC-NE3, JLab E89-008 and CLAS — published
- More results from E89-008, CLAS — coming soon
- JLab E02-019 — coming soon
- JLab@12GeV - DIS at x>1 — future

"Beam in 30 minutes or it's free"

Recent JLab experiments

E89-008: 1996 - 4 GeV (short run)

^{2}H, Carbon, Iron, Gold, θ=15-55^{o}

Measured σ at x>1, emphasis on

broadest possible x, Q^2 range for Iron

CLAS E2a,E2b: 2.2 and 4.5 GeV

^{3}He, ^{4}He, Carbon, Iron, $\theta \cong$ 20-30^{o}

Extracted A/^{3}He ratios for x>1

E02-019 (x>1) and E03-103 (EMC-He):
2004 - 6 GeV

^{1}H, ^{2}H, ^{3}He, ^{4}He, ^{9}Be, ^{12}C, ^{27}Al, ^{63}Cu, ^{197}Au

Measured σ at θ=18,22,26,32,40,50^{o}

Extract σ and ratios, 0.3<x<1, <1% statistics

EMC effect in ^{3,4}He, constraints on σ_n

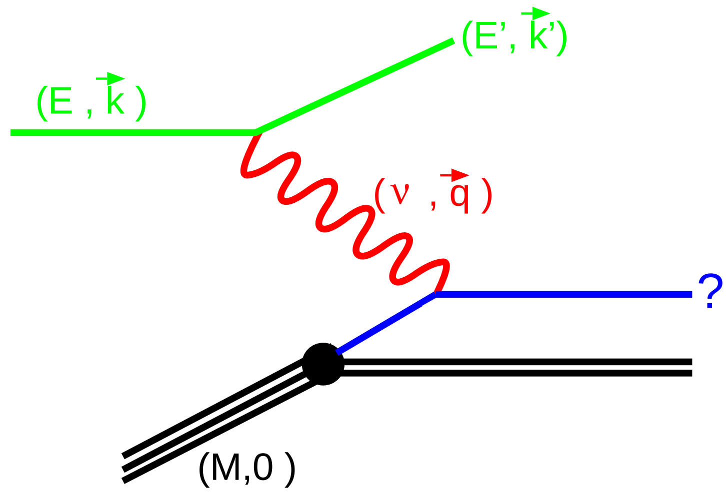
Extract σ and ratios for x>1, emphasis on:

Deuterium for x-->2

He-3 for x-->3

Inclusive e-A Scattering

In certain kinematic regions, the inclusive scattering is dominated by scattering from a quasifree constituent.



Where this simplified picture of the structure is valid, we see scaling and we can measure the parton distributions.

At high ν, q, scatter from a single quark.

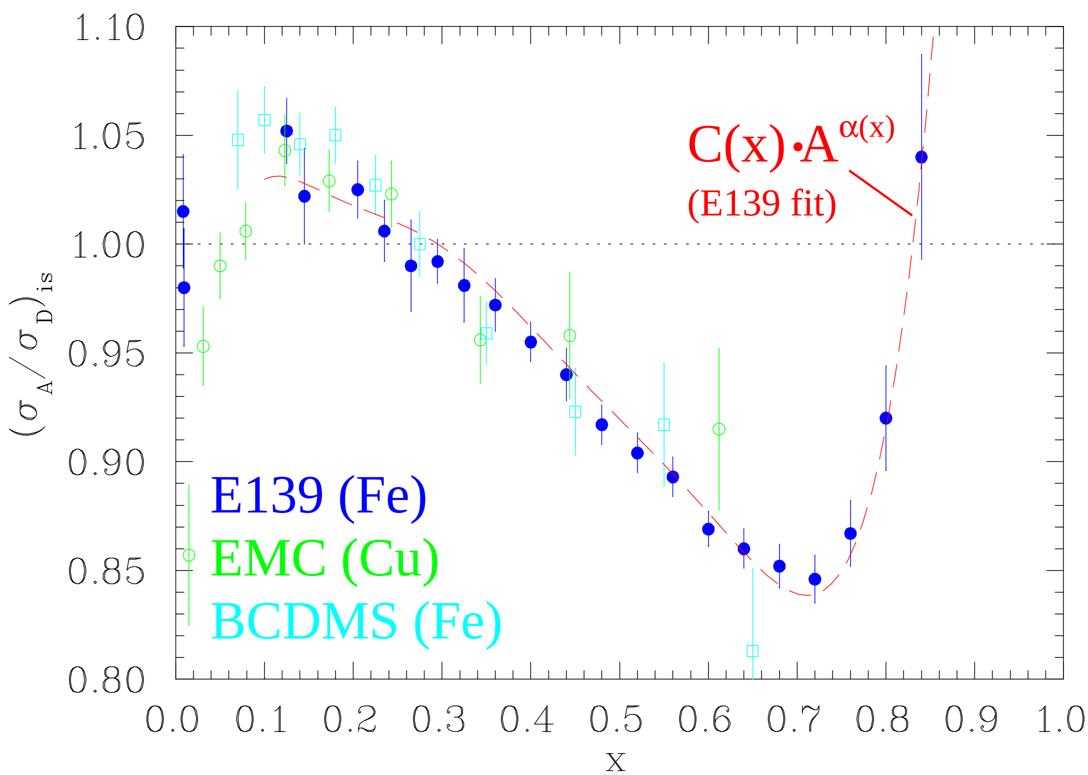
- $F_2(\nu,q)$ --> $F_2(x)$ $(F_2 \sim \sigma / \sigma_{e\text{-}q})$
- *x is the momentum fraction of the struck quark.*
- *$F_2(x)$ related to quark momentum distributions.*

At lower ν, scatter from a nucleon.

- $F(\nu,q)$ --> $F(y)$ $(F \sim \sigma / \sigma_{e\text{-}N})$
- *y is the longitudinal momentum of the nucleon.*
- *F(y) related to nucleon momentum distributions.*

F_2^A/F_2^D - The EMC Effect

The EMC collaboration first measured non-trivial nuclear dependence to structure functions



Significant data exists for Q^2>5 (GeV/c)^2 on heavy nuclei

- Deviation from unity in the ratio depends on x_{Bj}
- Shape is independent of A (A>4), but magnitude varies
- The effect has little Q^2-dependence

Limited data for light nuclei (A<9)

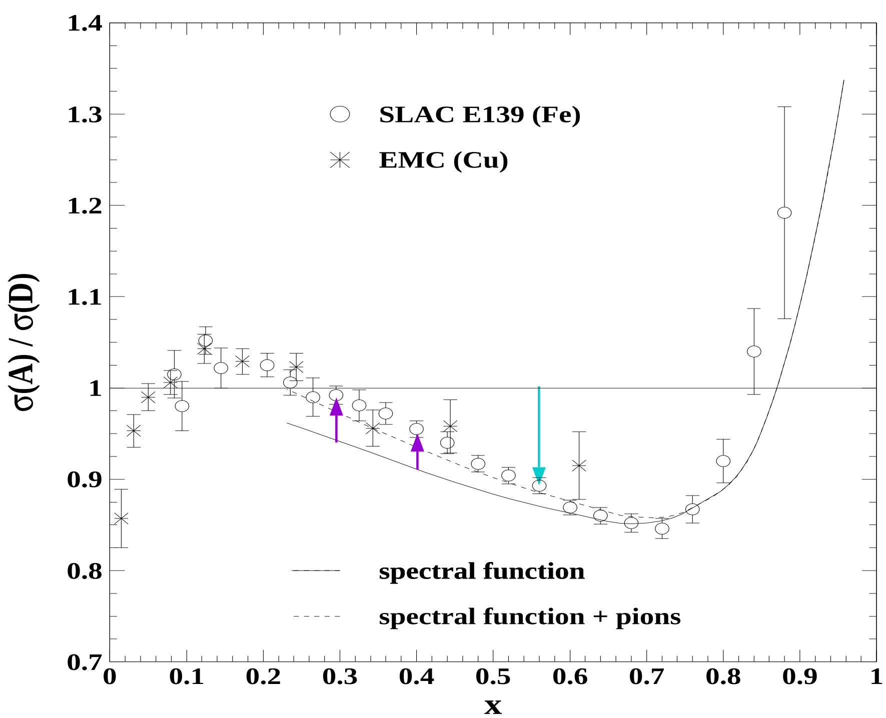
Limited data for large x (x>0.8)

Binding and Fermi motion

Binding, Fermi motion must be considered at ALL x values

Poor quality data at large x, uncertainty in nuclear structure in heavy nuclei --> few realistic calculations

Most calculations for infinite nuclear matter or fermi gas



O. Benhar and V. Pandharipande

If one has a reliable calculation of binding, Fermi motion, then what we want to explain is THIS, not THIS

E03-103: Provide high precision EMC ratios for ^3He, ^4He
Improve measurements at very high-x

Ran in Fall 2004, JA and D. Gaskell spokespersons

Importance of EMC effect in light nuclei

Less uncertainty in evaluating models of the EMC effect

Current data do not differentiate between dependence on nuclear size, A, or nuclear density, ρ

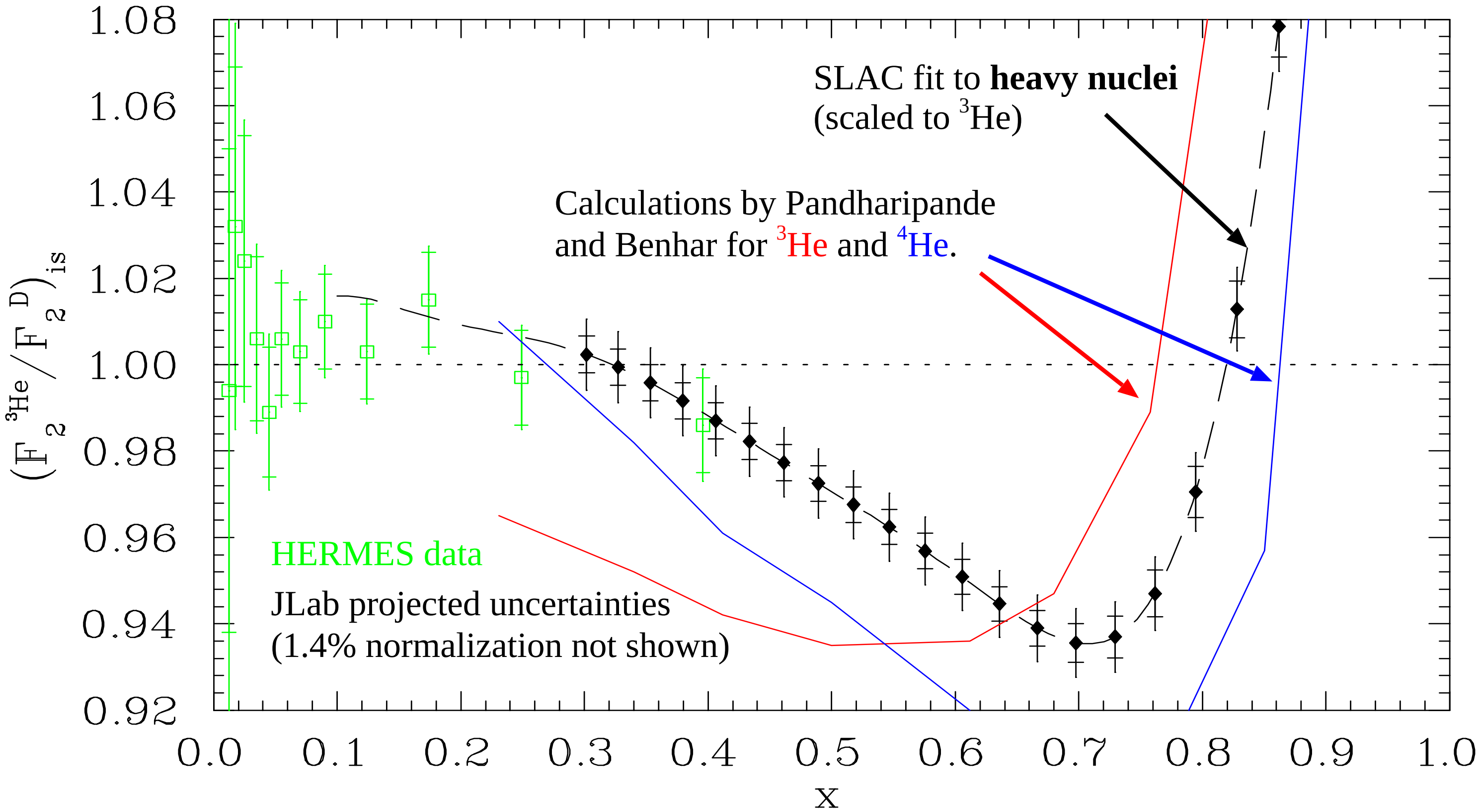
The x-dependence is universal in heavy nuclei, but predicted to be very different for A=3,4

Goals of E03-103:

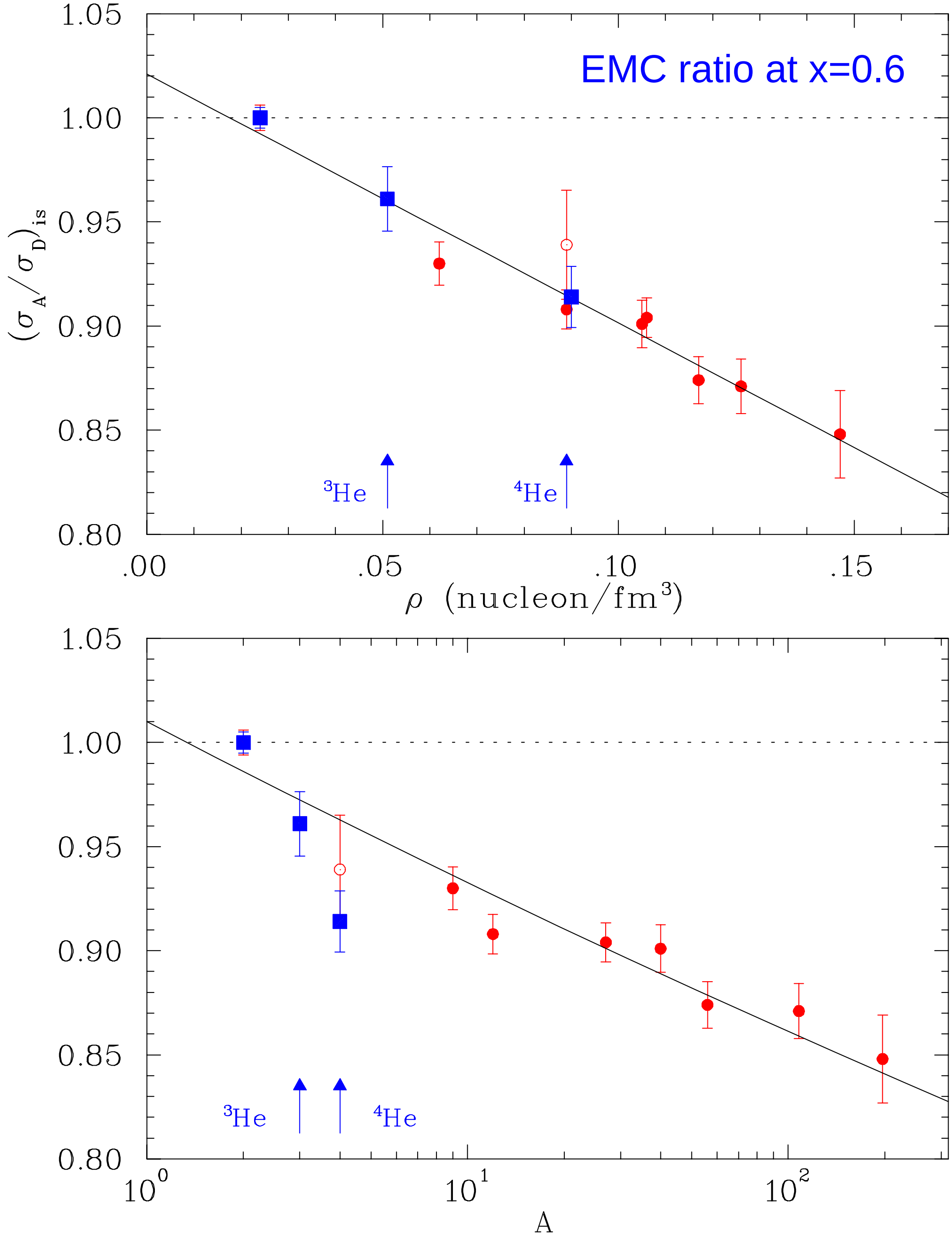
*Measure ***shape*** of EMC effect in very light nuclei

- **May be very different than for heavy nuclei**
- **Better than factor of two improvement for ^{4}He**
- **First data on ^{3}He at large values of x**

*Test models of the EMC effect in ***few-body calculations***



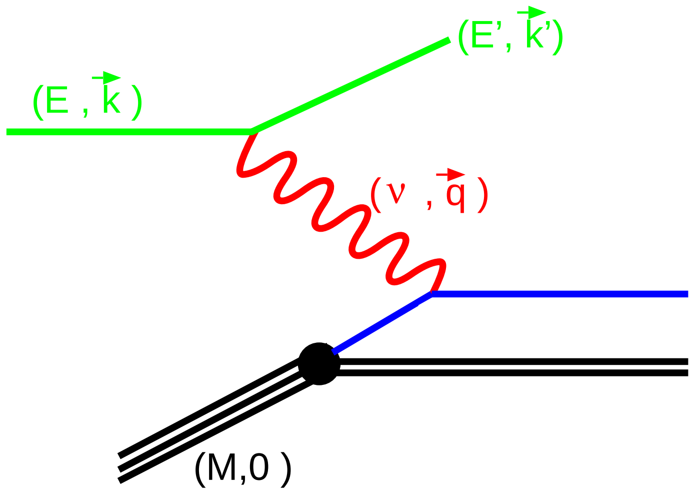
Projected Uncertainties on A-dependence of EMC effect



Factor of two improvement over E139 for ^{4}He

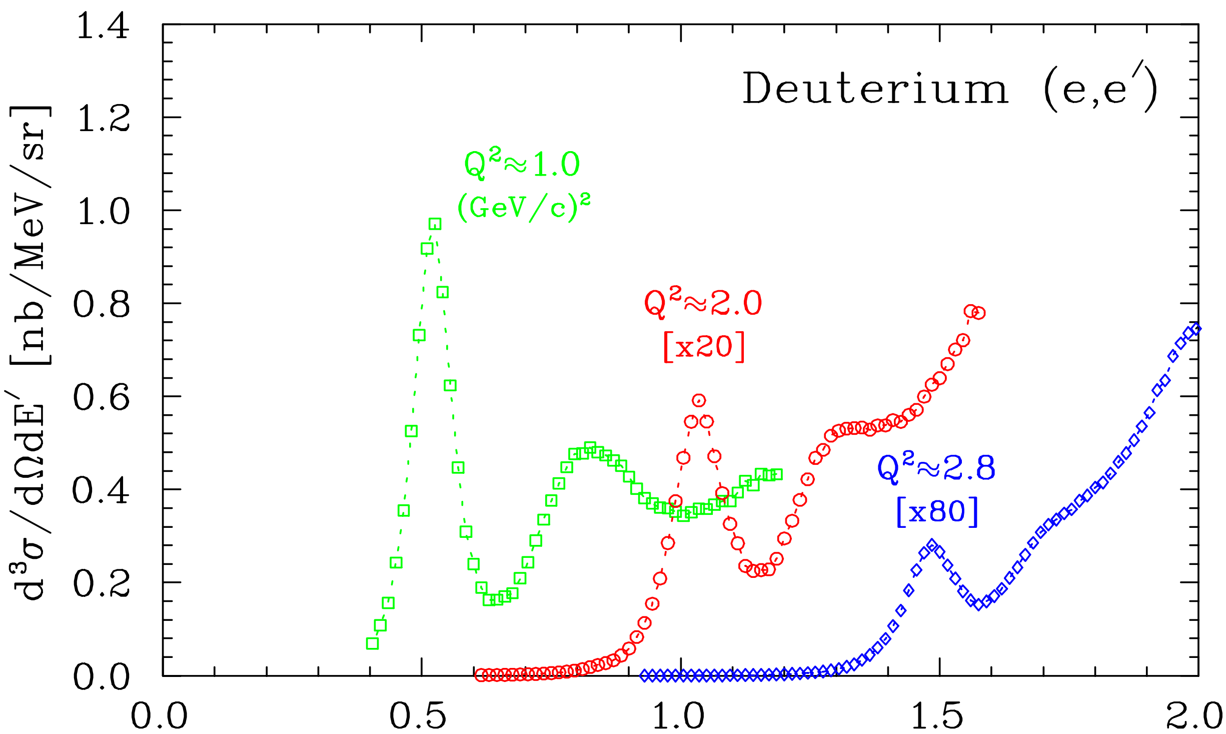
Completely new measurement for ^{3}He

Inclusive e-A Scattering, QE region



$$\nu = E - E'$$
$$\vec{q} = \vec{k} - \vec{k}'$$
$$Q^2 = q^2 - \nu^2$$
$$x_{Bj} = \frac{Q^2}{2M\nu}$$

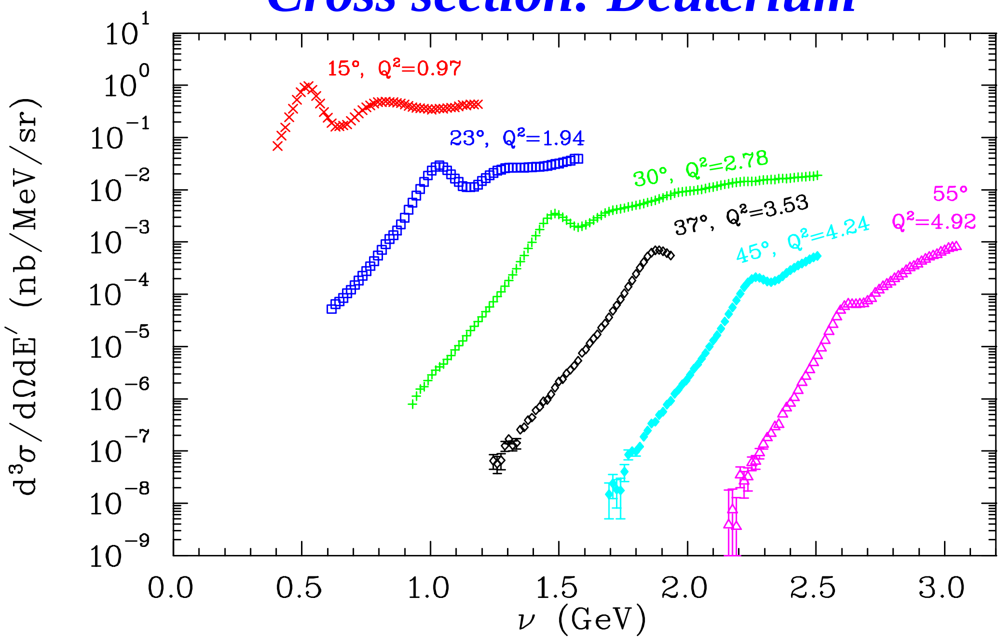
In certain kinematics, the electron-nucleus scattering is dominated by scattering from a quasifree nucleon



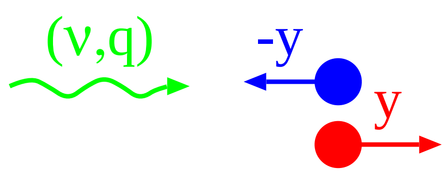
$x \approx 1$ corresponds to quasielastic scattering

Elastic electron-nucleon scattering, 'smeared' by the nucleon momentum distribution, nuclear binding

Cross section: Deuterium



y = initial nucleon momentum along q



$$\nu + M_D = \sqrt{M_N^2 + (q-y)^2} + \sqrt{M_N^2 + y^2}$$

Remove interaction to isolate nuclear structure

$$F(y,q) \sim \sigma_{e\text{-}A} / \langle\sigma_{e\text{-}N}\rangle$$

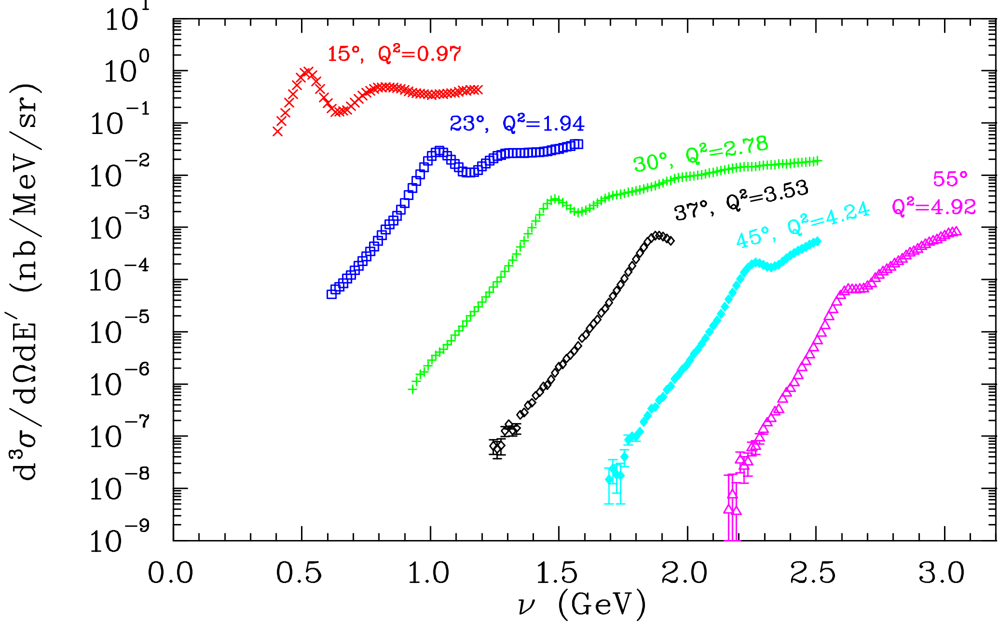
PWIA predicts y-scaling for quasielastic scattering at large *q*:

- The scaling function, F, depends only on |y|
- F(y) <---> n(k), the nucleon momentum distribution

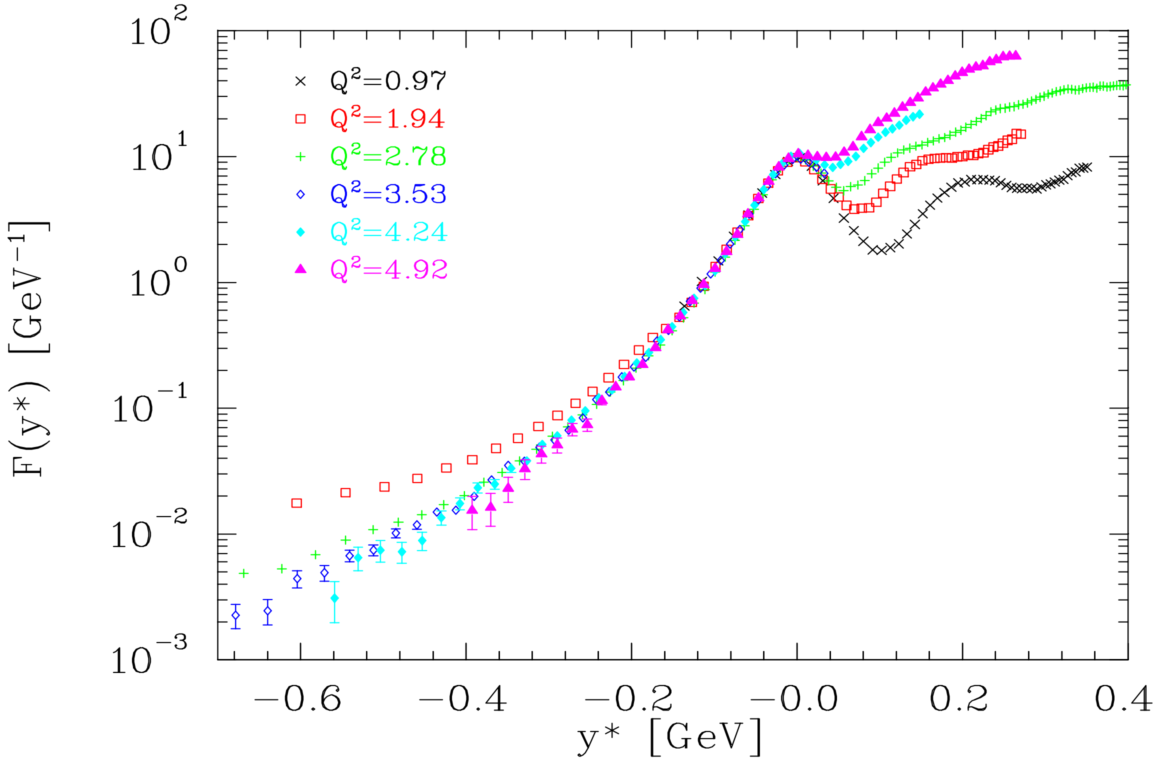
Main assumptions:

Quasi-elastic scattering	[low energy transfer]
No FSI	[inclusive, high Q^2]
Unexcited (A-1)spectator system	[deuterium]

Cross section: Deuterium



F(y,q) ~ $\sigma_{e\text{-}A}$ / <$\sigma_{e\text{-}N}$> ***y = initial nucleon momentum along q***

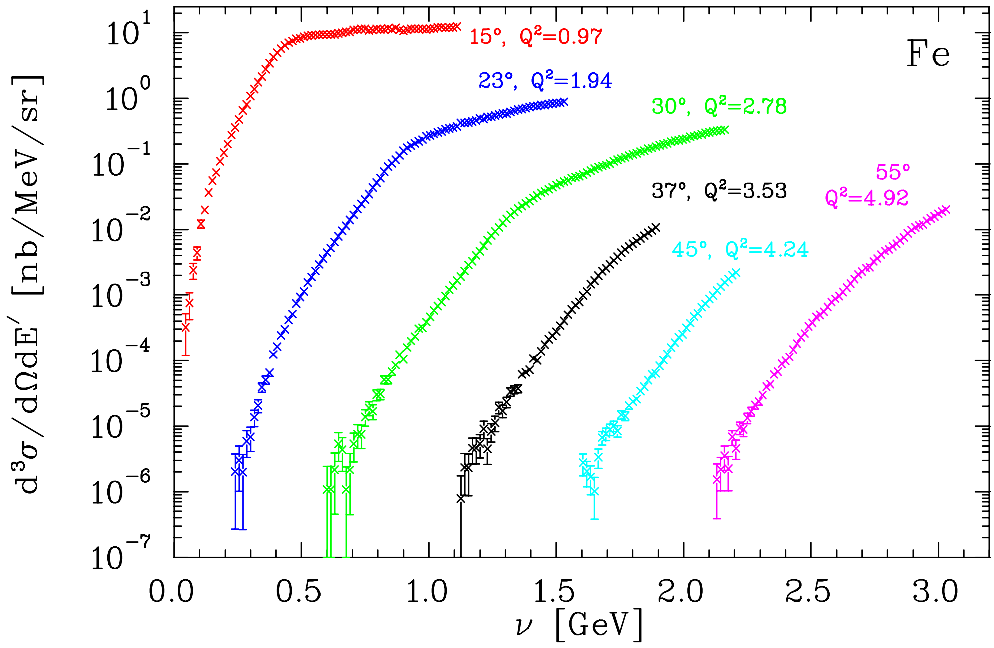


PWIA predicts y-scaling for quasielastic scattering at large *q*:

The scaling function, F, depends only on |y|

F(y) <---> n(k), the nucleon momentum distribution

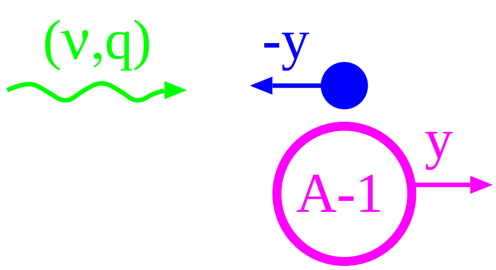
Cross section: Iron



y = initial nucleon momentum (along q)

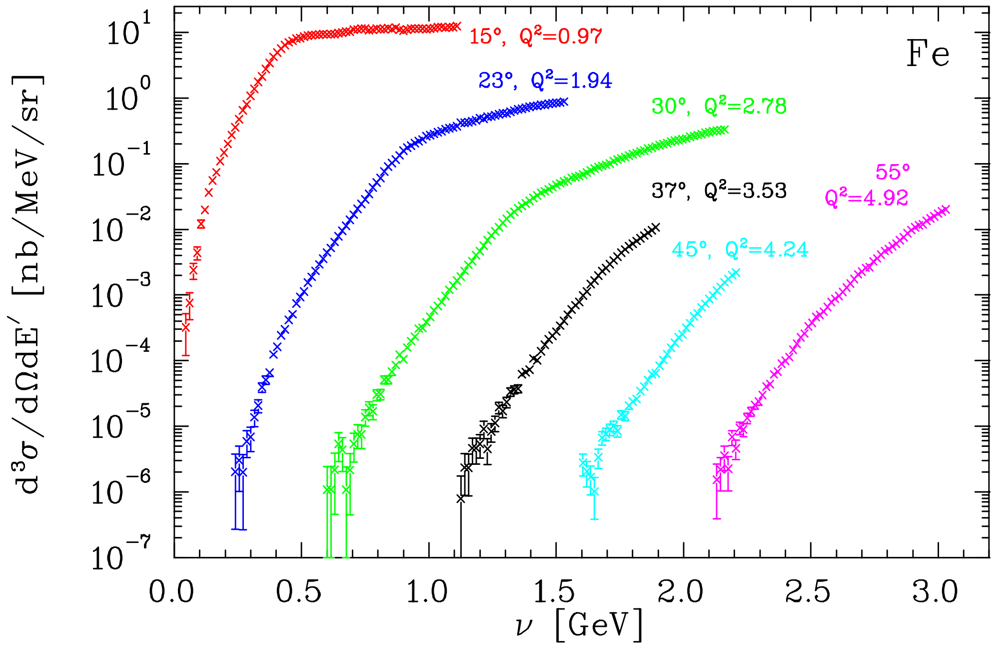
F(y,q) ~ $\sigma_{e\text{-}A} / \langle\sigma_{e\text{-}N}\rangle$

Usual y-scaling approach:



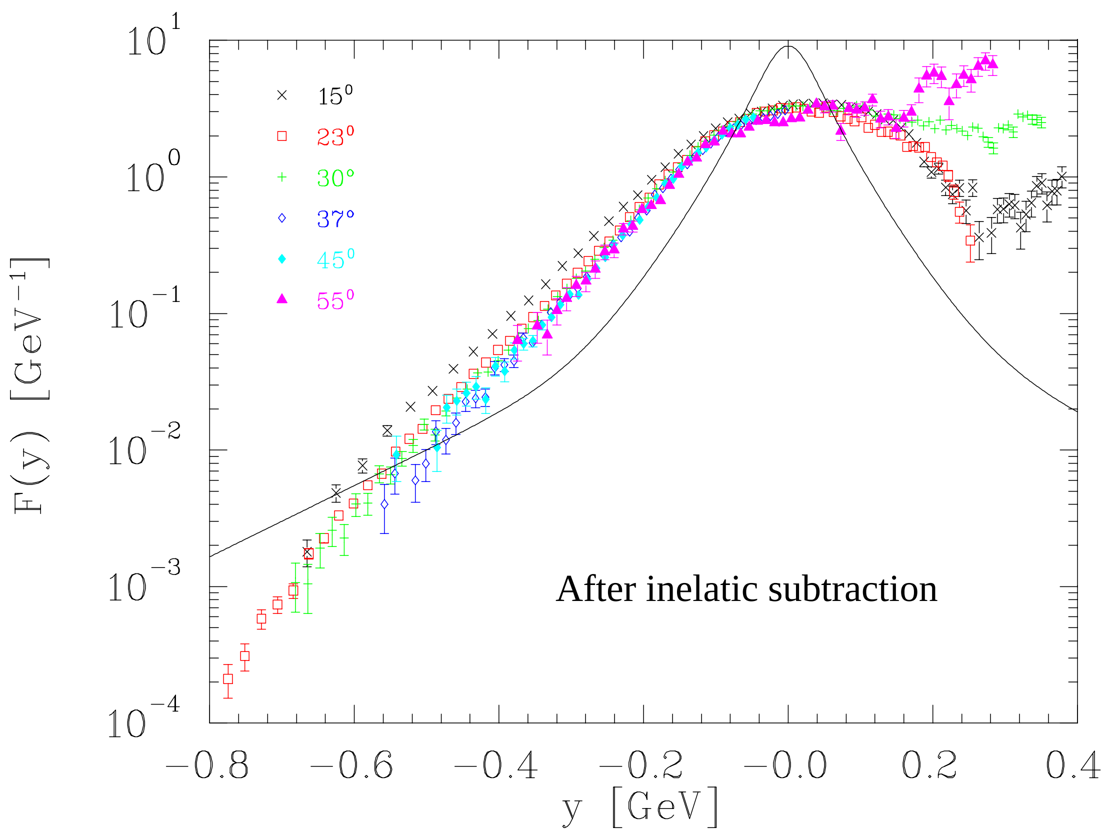
$$\nu + M_D = \sqrt{M_N^2 + (q-y)^2} + \sqrt{M_{A-1}^2 + y^2}$$

Cross section: Iron



y = initial nucleon momentum (along q)

F(y,q) ~ $\sigma_{e\text{-}A}$ / <$\sigma_{e\text{-}N}$>

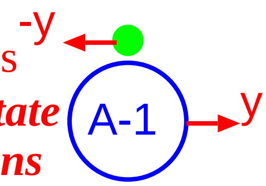


Assumption of unexcited A-1 spectator is inconsistent with picture of short range correlations generating large momenta

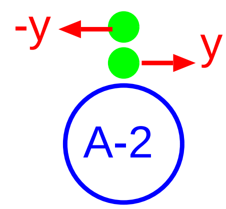
Definition of y for A>2

y is the longitudinal momentum of the struck nucleon, and is determined by energy conservation.

Normal y: Assumes struck nucleon + recoiling (A-1) nucleus
This ***assumes the spectator A-1 system is in an unexcited state***
Reasonably good approximation for ***low momentum nucleons***



NN interactions will lead to high momentum nucleons whose momentum is balanced by a single nucleon, leading to ***an excited (A-1) nucleus***



The excitation of the residual nucleus can be taken into account by calculating binding corrections:

$$F(y) = f(y) + B(y)$$

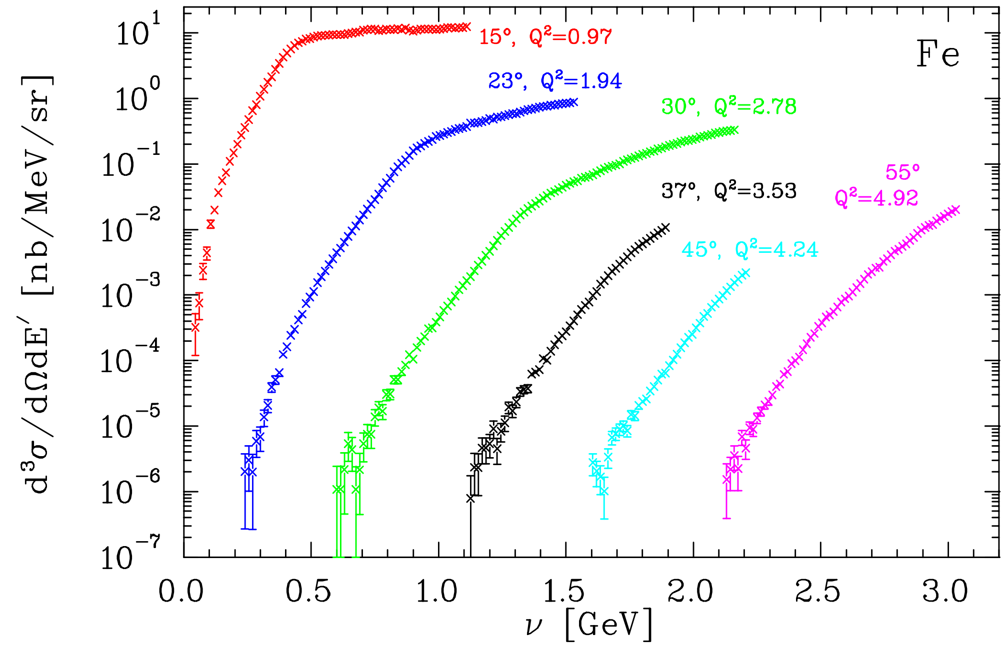
Rather than correcting the scaling *function*, we can change the calculation of the scaling *variable*.

We will use a three-body breakup picture to calculate the nucleon momentum. Unlike the picture above, we allow the correlated pair to move in the mean field of the A-2 nucleus.

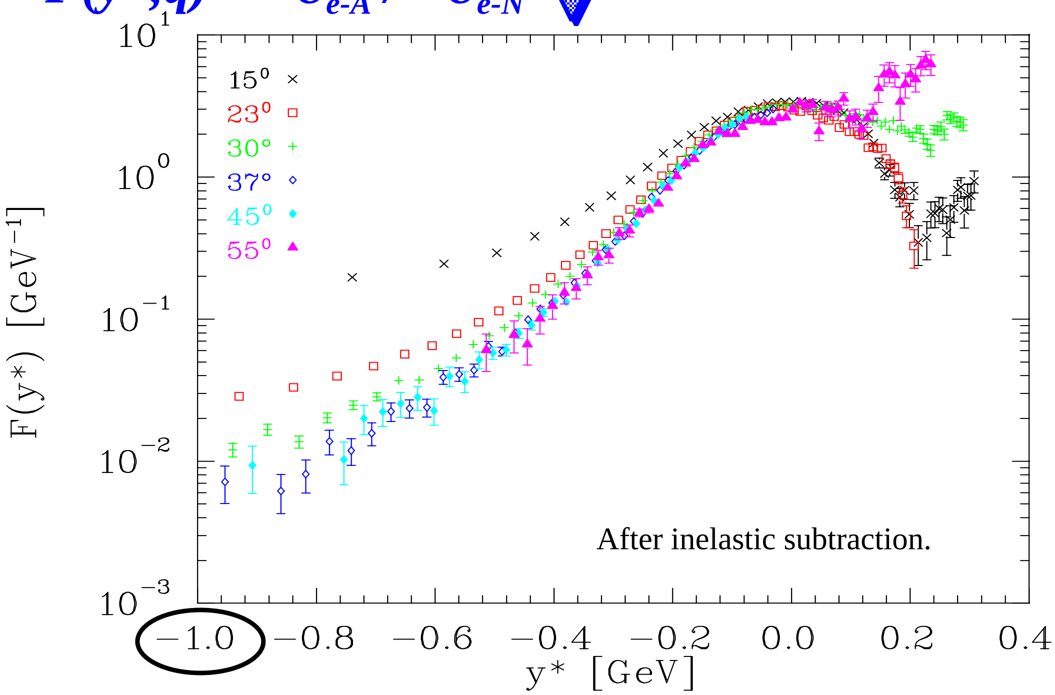
$$y^* = y + K_{pair} / 2$$

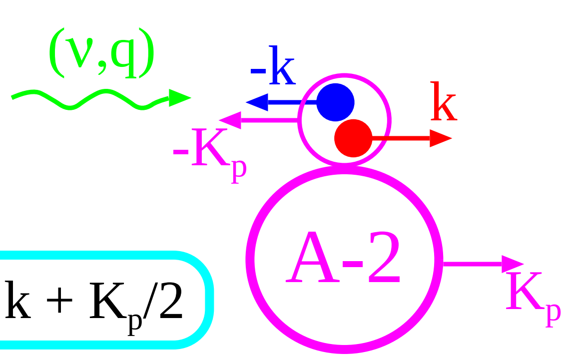
Similar to y_{CW}, *C. Ciofi degli Atti and G. B. West, PLB458:447 (1999)*

Cross section: Iron



$F(y^*,q) \sim \sigma_{e\text{-}A} / \langle\sigma_{e\text{-}N}\rangle$



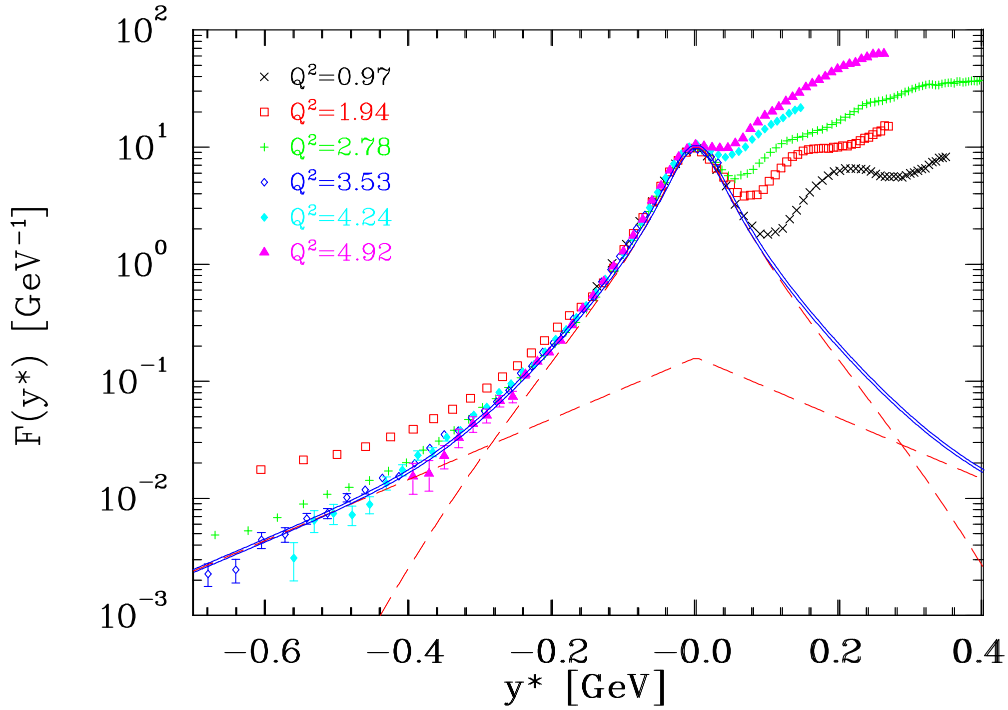


$$\sqrt{M_N^2 + (q - k - K_p/2)^2} + \sqrt{M_N^2 + (k - K_p/2)^2} + \sqrt{M_{A-2}^2 + K_p^2}$$

$y^* = k + K_p/2$

Final state interactions at large |y*|?

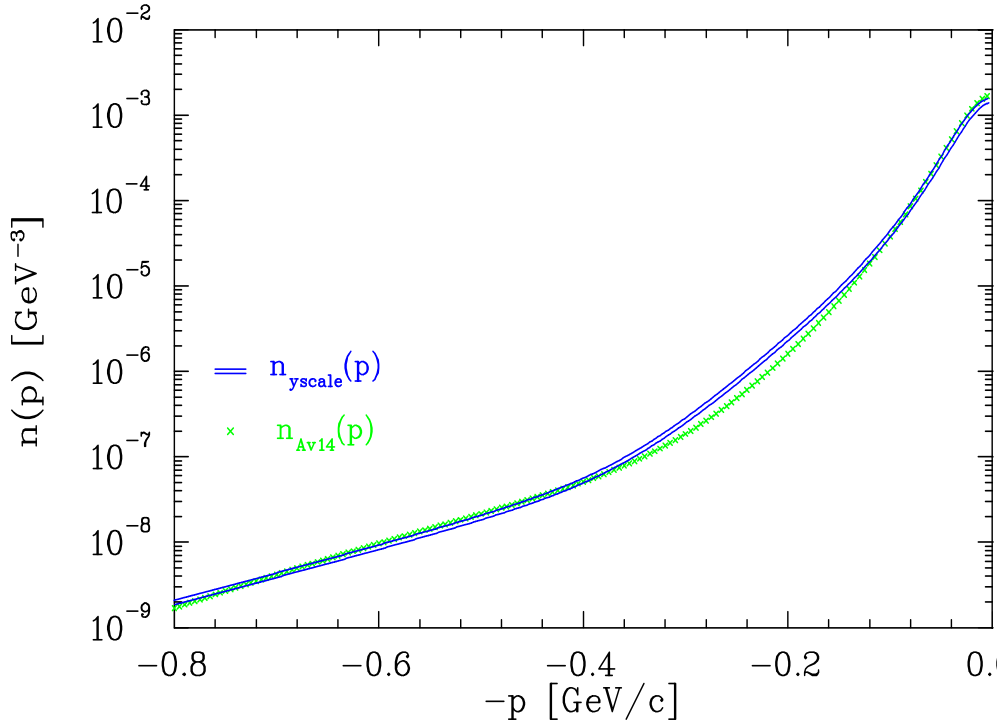
F(y*) for deuterium



Limited data in scaling region for large |y*| values

Use *fit* to F(y*) to extract momentum distribution

Extracted momentum distribution



Good overall agreement with calculated n(p)

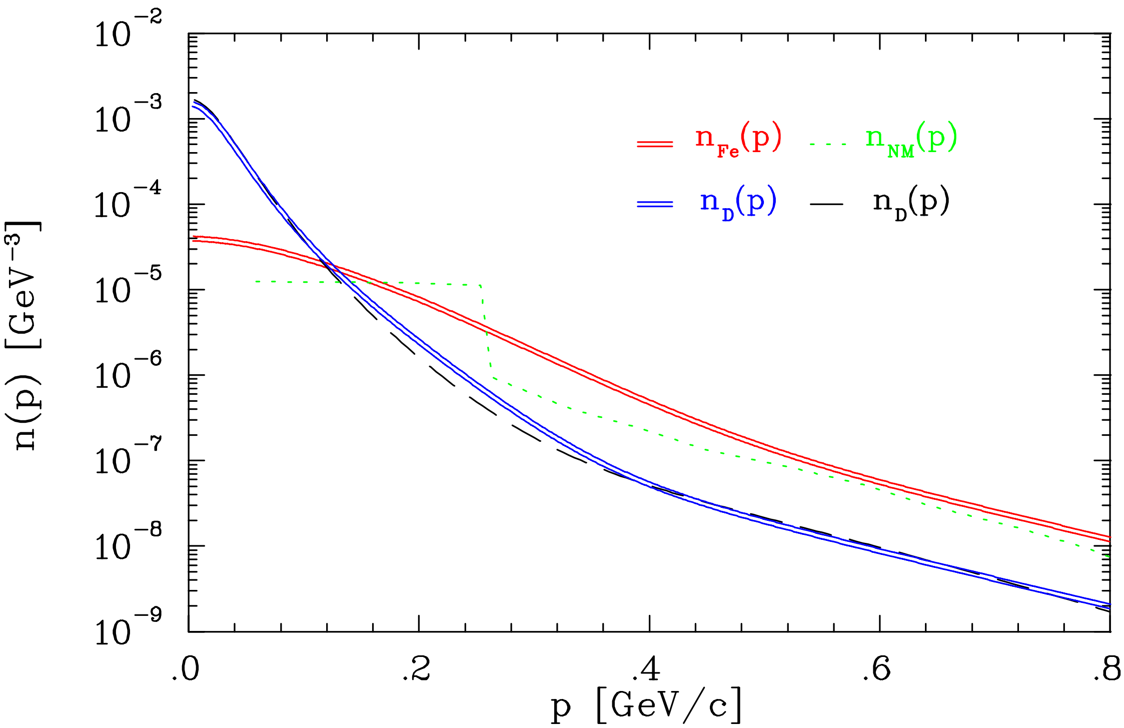
Normalization in tail hints at little or no FSI

poor quality of deuterium data --> not much detail at large |y|

Momentum Distributions.

y*-scaling extraction for Deuteron and Iron

Calculations for Deuteron and infinite nuclear matter



Same high momentum behavior seen is for C, Au

Distribution at high momentum has same shape for deuteron and heavy nuclei: 2N SRCs appear to dominate

Same can be seen in cross section ratios, σ_A/σ_D at large x

- By x=1.5, the mean field (Fermi motion) contributions are negligible
- If only 2N SRCs contribute in heavy nuclei, then the ratio of A/D should be constant above x=1.5

Medium Modification (nucleon 'swelling')

y-scaling data often quoted as setting strong limit on nucleon medium modifications

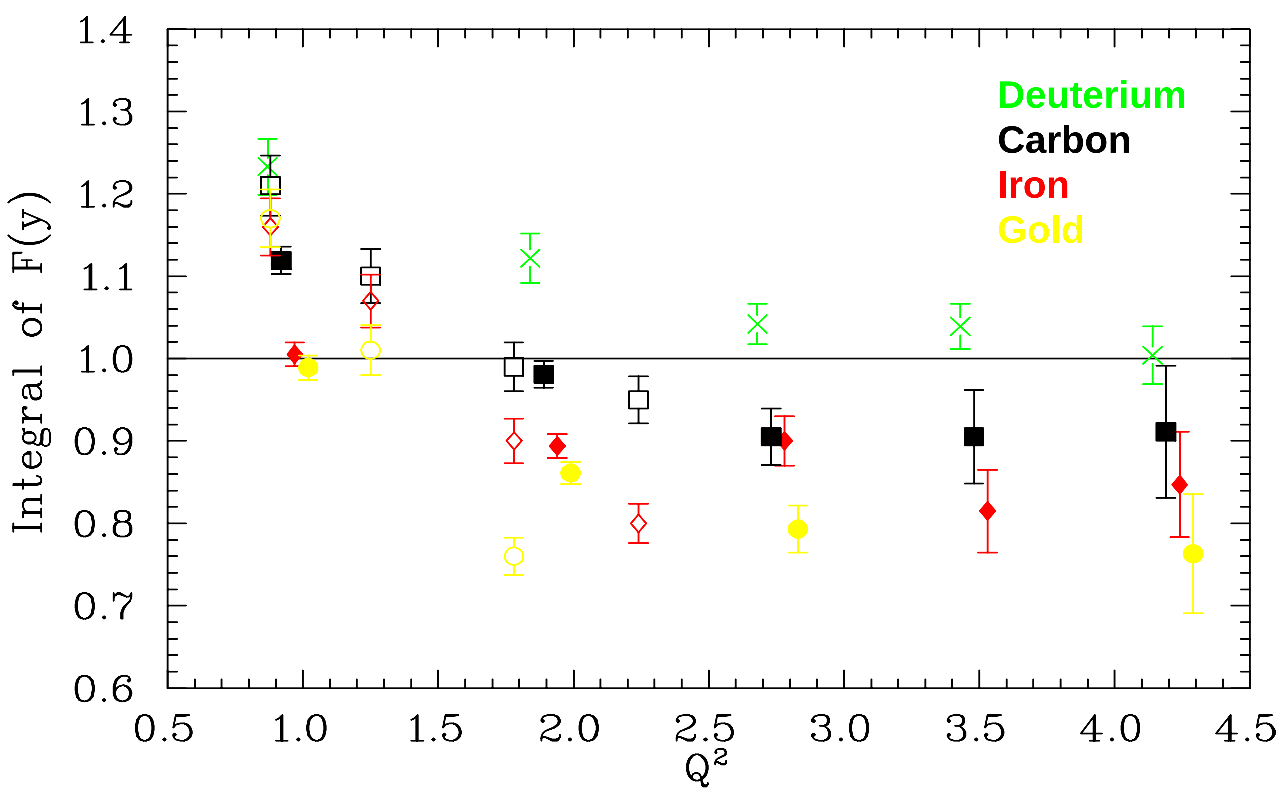
I. Sick, NPA 434:677 (1985)
R. D. McKeown, PRL 56, 1452 (1986)

The normalization condition for n(p) provides a sum rule for the integral of F(y)

$$2\int_{-\infty}^{0} F(y)\, dy = 1$$

Violations of this sum rule might indicate

- Scaling violation due to FSI, Inelastic contributions
- Medium modification of nucleon form factors. [$F(y) \sim \sigma / \bar{\sigma}_{eN}$]



There is a clear decrease with target mass (density)

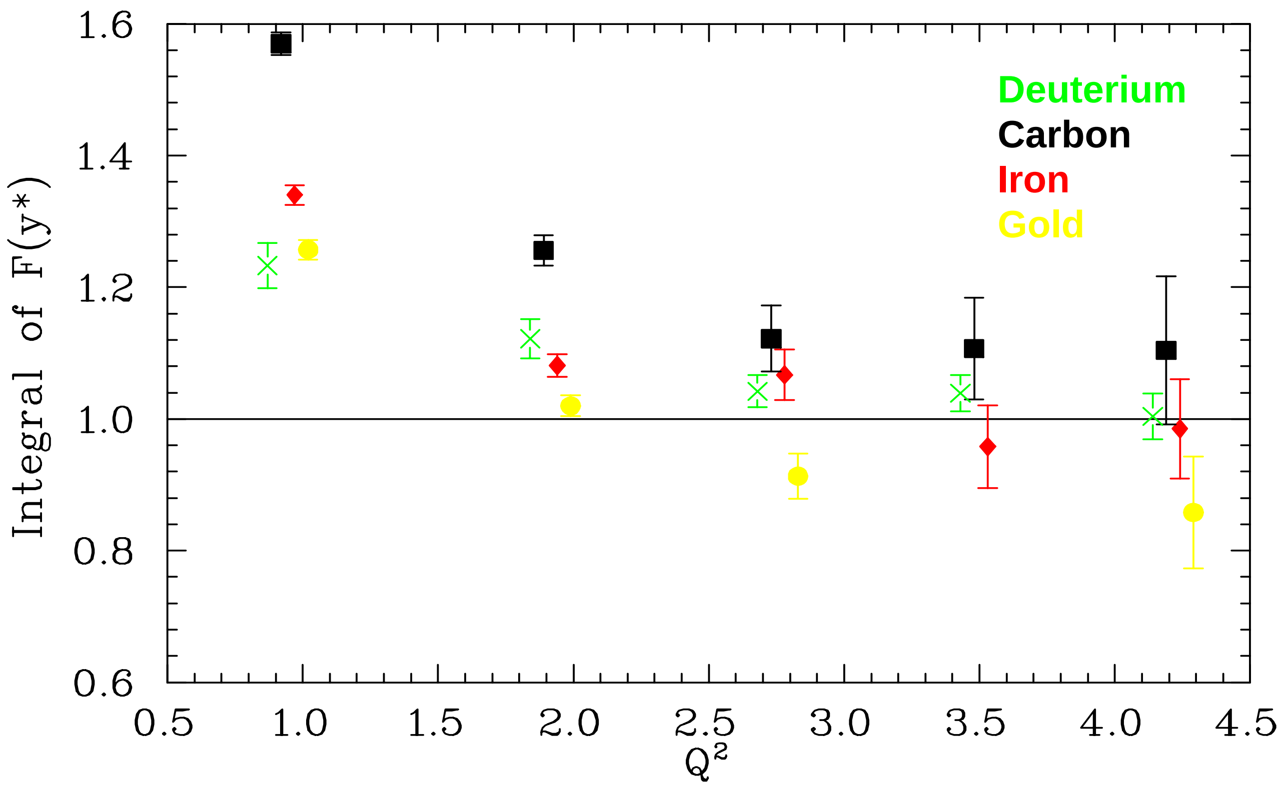
Nucleon medium modifications?

Nucleon 'swelling'?

Before we take this as evidence of medium modifications, we need to check other possibilities

We already know that the usual y does not properly model the excitation of the spectator nucleus

Look at integral of F(y*):



Still have large deviations from unity at low Q^2 (FSIs)

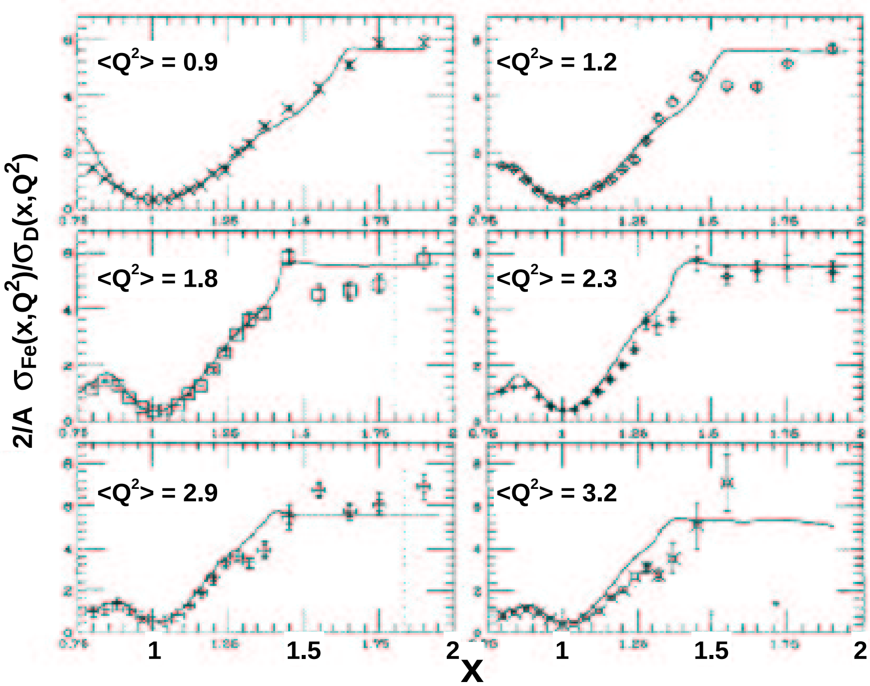
Consistent with unity at large Q^2 - no indications of swelling

SRCs in σ_A/σ_D Ratios

σ_A/σ_D ratios show that heavy nuclei and deuterium have similar high momentum tails in regions where mean field motion is negligible (x>1.5).

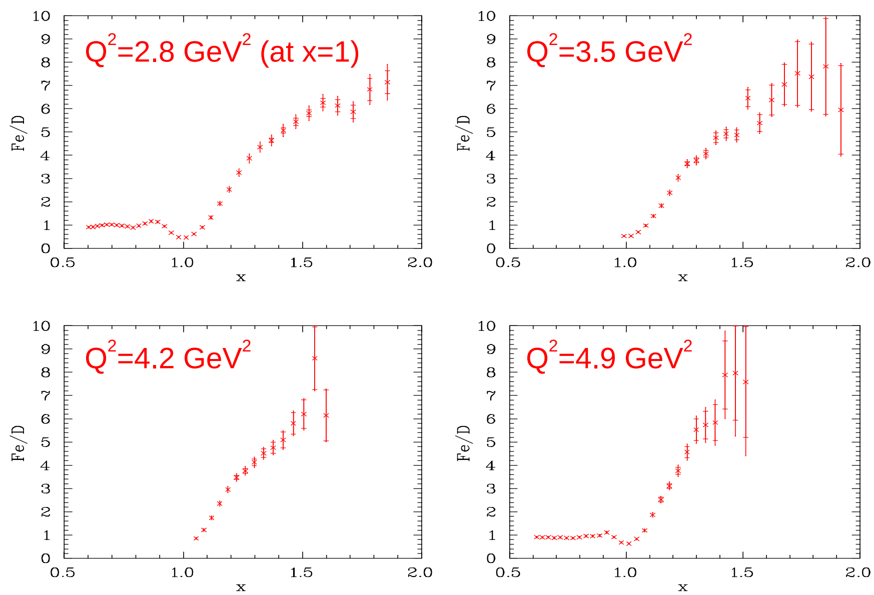
SLAC

Fe data from SLAC-NE3, Deuterium from previous SLAC experiments



JLab E89-008

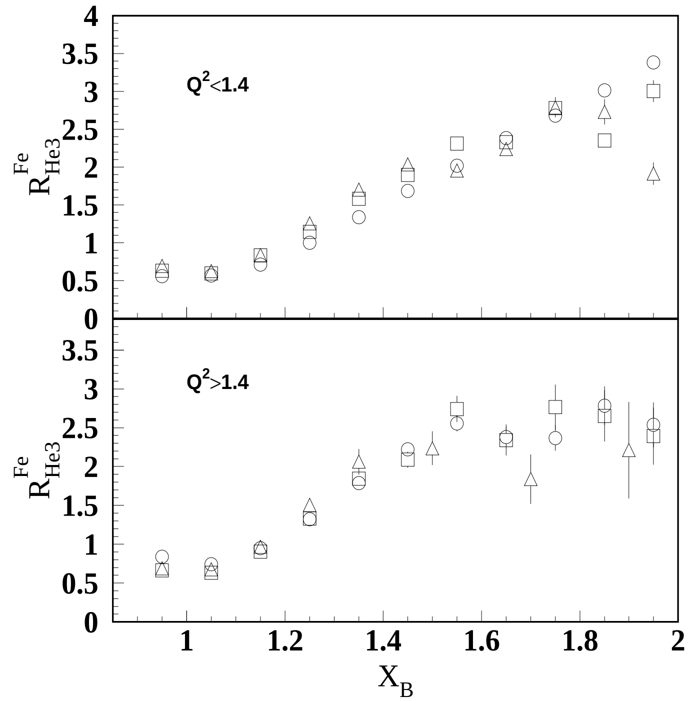
Ratios limited by lack of high-x deuterium data



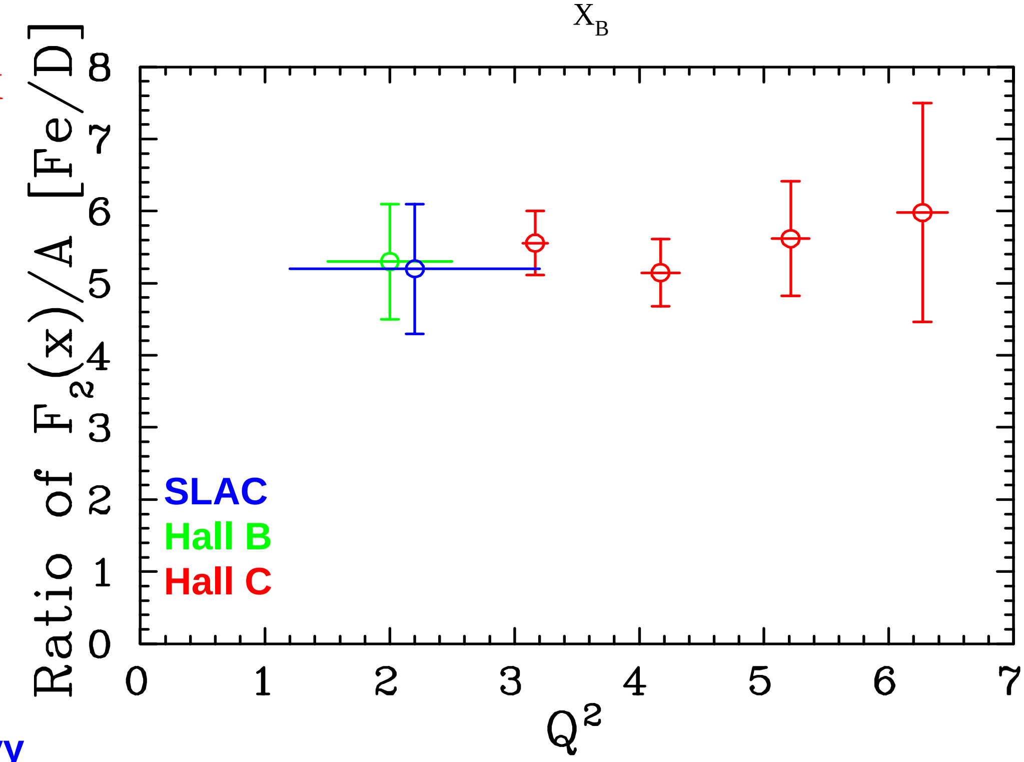
A plateau in σ_A/σ_{He-3} at larger x values would provide strong indication of multi-nucleon correlations

Requires data on ^{3}He, and data at higher x (x>2.5)

CLAS data, $Fe/^3He$



F_2^{Fe}/F_2^D at large x



SLAC - Combined deuterium and heavy target data from different experiments. Limited Q^2 coverage

Hall B - Measured ratios of heavy targets to He-3, rely on measurements or calculations of 3He/D ratio. Good x-coverage, limited Q^2 range

Hall C - Limited deuterium data, so x-coverage is poor at highest Q^2 values

CLAS data, PRELIMINARY ratios of A/^{3}He show plateaus in in 2N ***and*** 3N dominated regions

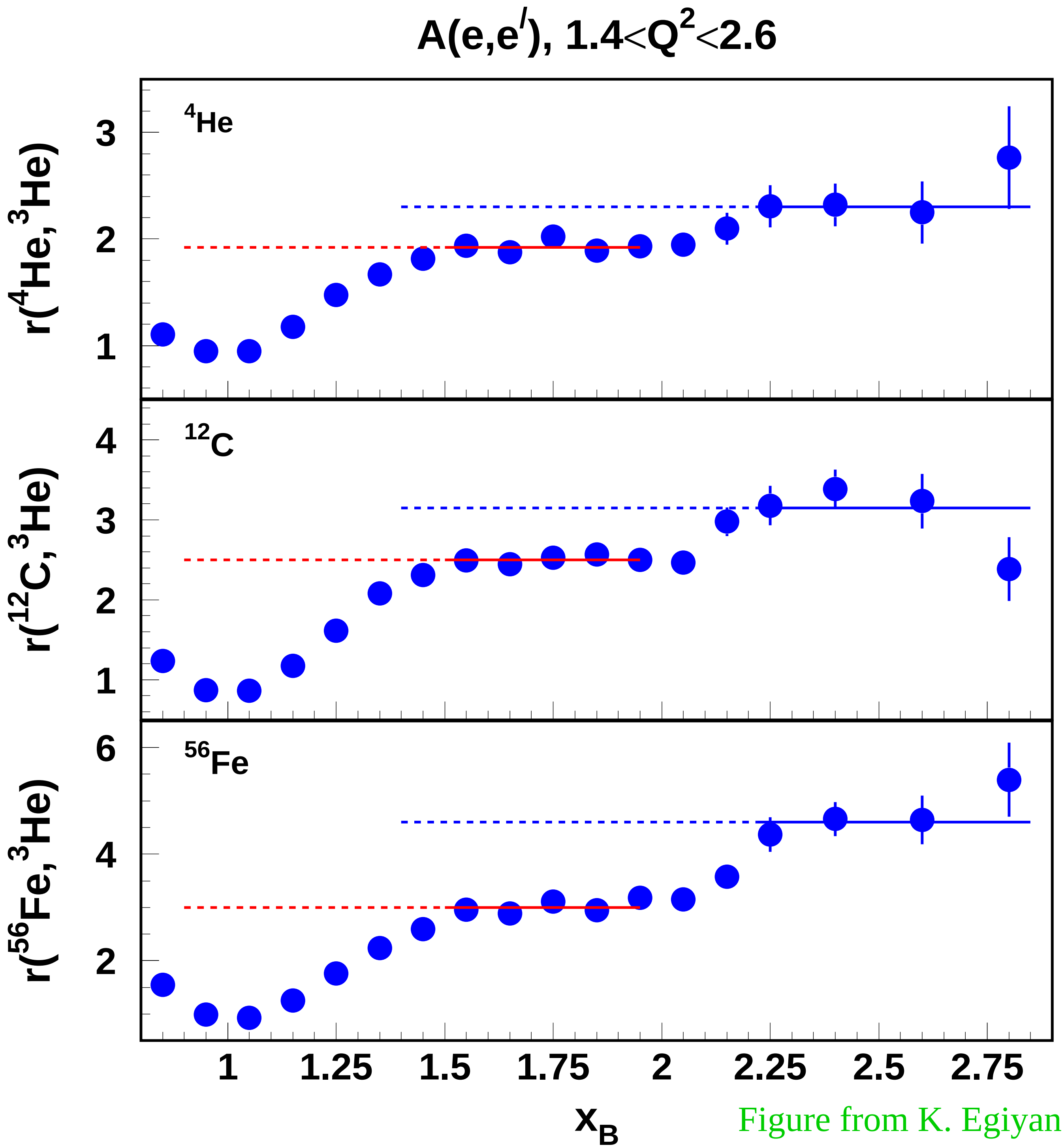


Figure from K. Egiyan

Cross section ratio related to ratio of SRCs relative to D (^{3}He)

After including coulomb distortion, motion of the correlated pair, correction for σ_n/σ_p

We can also compare the data to complete calculations that include FSIs, inelastic contributions, etc...

Use high-x cross sections to constrain the high-momentum spectral function

Look for signature of 2N, multi-nucleon SRCs

Dotted =mean field approx.

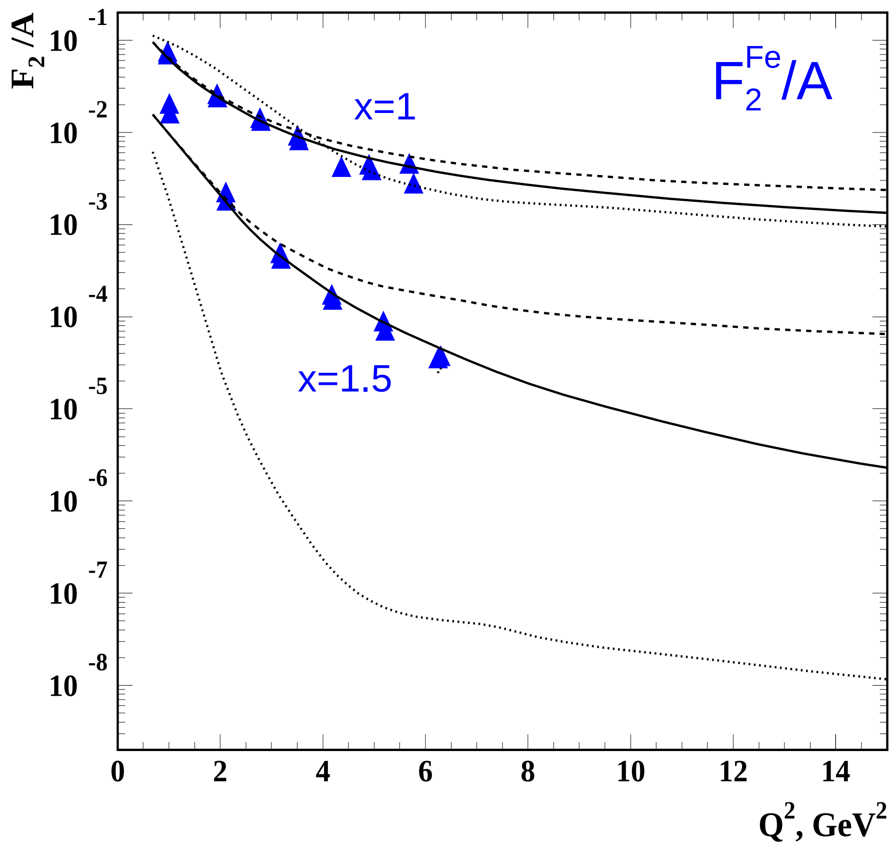
Solid = +2N SRCs.

-Frankfurt, Day, Sargsian, and Strikman, Phys. Rev. C (1993)

Dashed = +multi-nucleon.

-Frankfurt and Strikman, Phys. Lett. B94 (1980) 216

Need data on light nuclei to allow separation of nuclear effects from 2N, 3N correlations



We have to go beyond the PWIA scaling analysis, but the success of this simple picture helps identify the relevant degrees of freedom in the problem

Hints that FSIs, inelastic contributions will be small in full calculation

Important to understand where the PWIA analysis works and how it fails if we are going to rely on scaling when interpreting the data *e.g. as input to other PWIA calculations or if interpreted in terms of medium modifications ('nucleon swelling')*

E02-019: x>1 at 6 GeV

6 GeV extension will significantly extend these studies

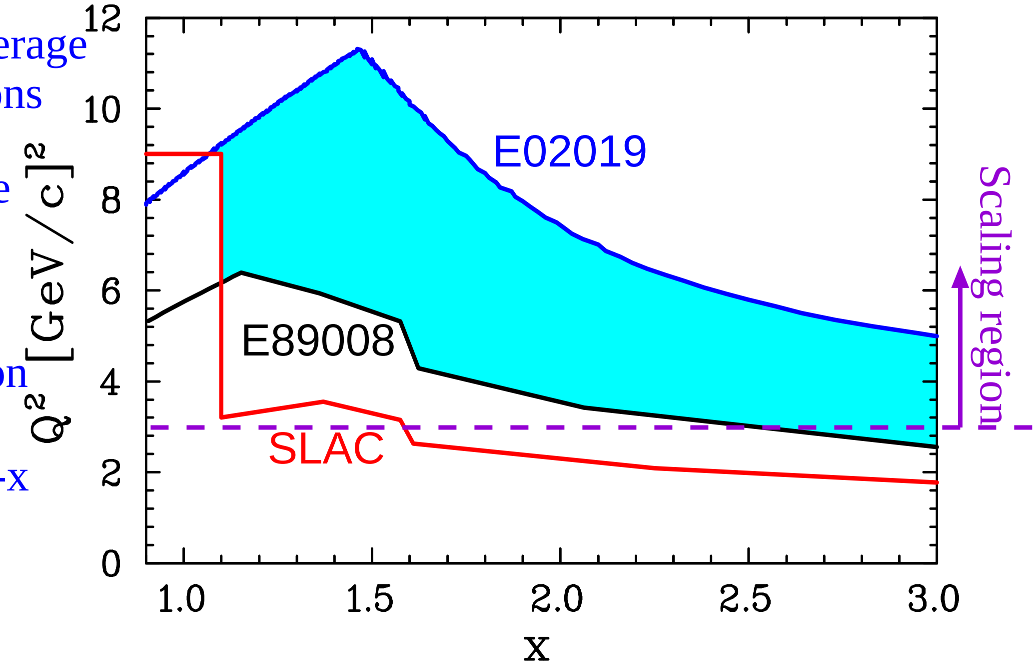
Finished late 2004: JA, D. B. Day, A. F. Lung, B. W. Filippone spokespersons

Large improvement in coverage for high momentum nucleons

^{2}H, ^{3}He, ^{4}He data to compare to few-body calculations

C, Cu, and Au to allow nuclear matter extrapolation

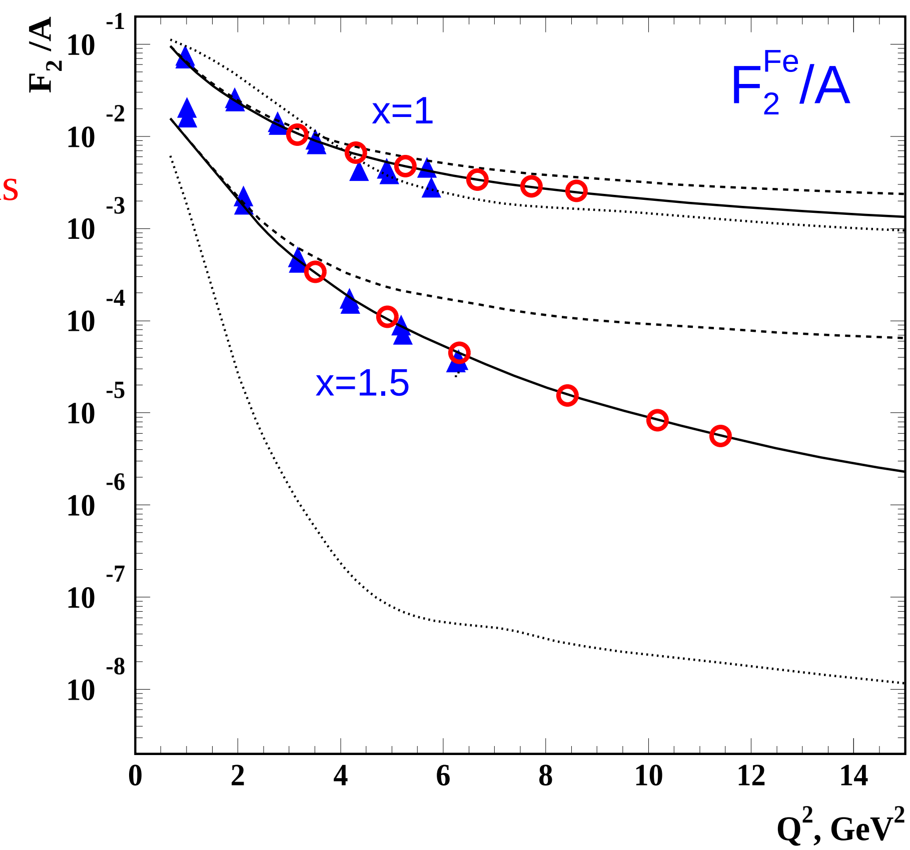
Use A/^{3}He ratios and high-x behavior to look for multi-nucleon correlations



Data on light nuclei will allow separation of nuclear effects from 2N, 3N correlations

E02-019 will measure both the A-dependence and the x-dependence

Projected uncertainties typically 3-5%



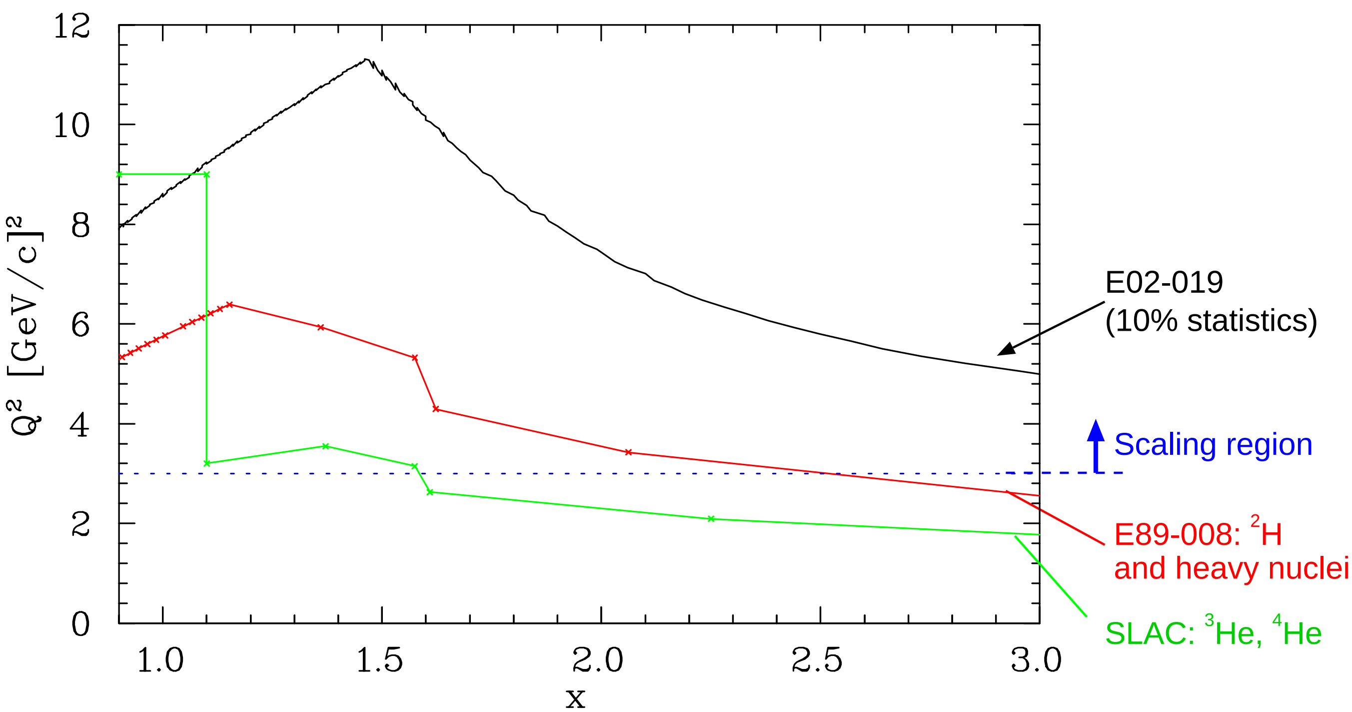
Scaling, n(p), and SRCs

The predicted ***scaling*** of F(y) is observed for all nuclei, but does ***not*** give a sensible momentum distribution for A>2

Wrong shape, normalization, high-p behavior

A modified definition of y (y*, y_{CW}) yields reasonable results

Reasonable momentum distribution (data up to ~1 GeV/c), 2N SRCs appear to dominate at high p, in agreement with ratios, calculations



New 6 GeV data will improve deuterium data at large x, significantly improve x, Q^2 coverage for ^{3}He and ^{4}He

The data will also be used to study

Distribution of high momentum nucleons, 2N and 3N SRCs

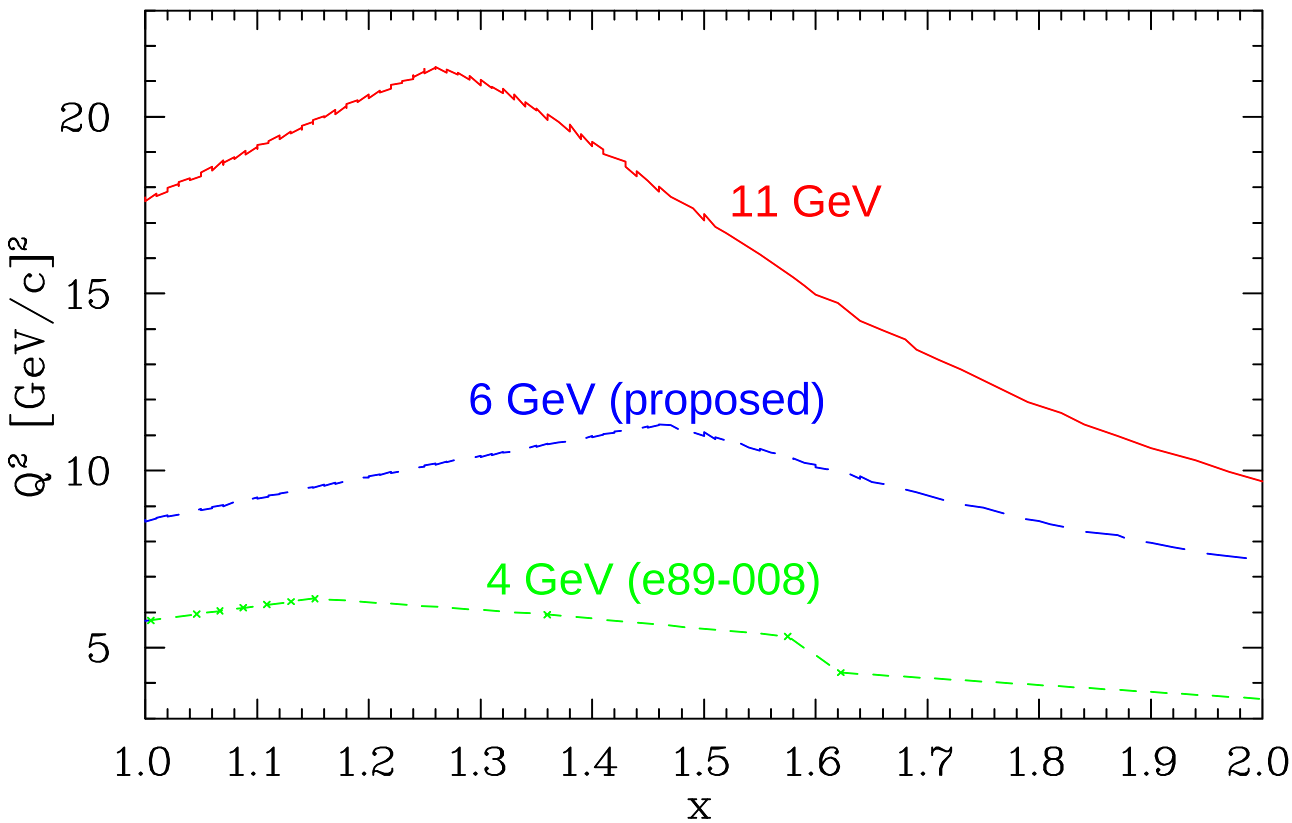
y-scaling, superscaling, final state interactions

ξ-scaling, local duality, higher twist in nuclei

QCD moments for nuclei (neutron), energy momentum sum rule

...and much more

x>1 at higher energies (JLab@12 GeV)



12 GeV also provides a *new* opportunity:

Quark distributions at x>1: 'superfast quarks'

Two measurements exist so far:

CCFR (ν-C): $F_2 \sim e^{-8x}$ (Q^2~100 GeV^2)

BCDMS (μ-Fe): $F_2 \sim e^{-16x}$ (Q^2~100 GeV^2)

These experiments have data in a limited range around x=1, and are limited by statistics or resolution

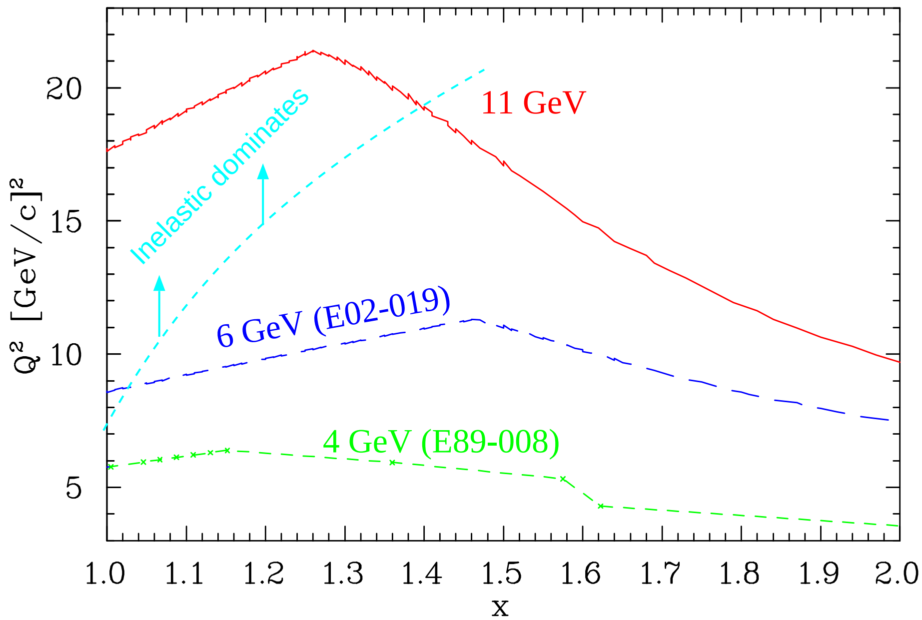
JLab@12 GeV will allow high precision measurements of the quark distributions for x>1

Jeffylab-12

"Beam in 2009 or it's free"

Deep Inelastic Scattering at x>1

With 11 GeV electrons cross section is inelastic dominated up to x~1.4



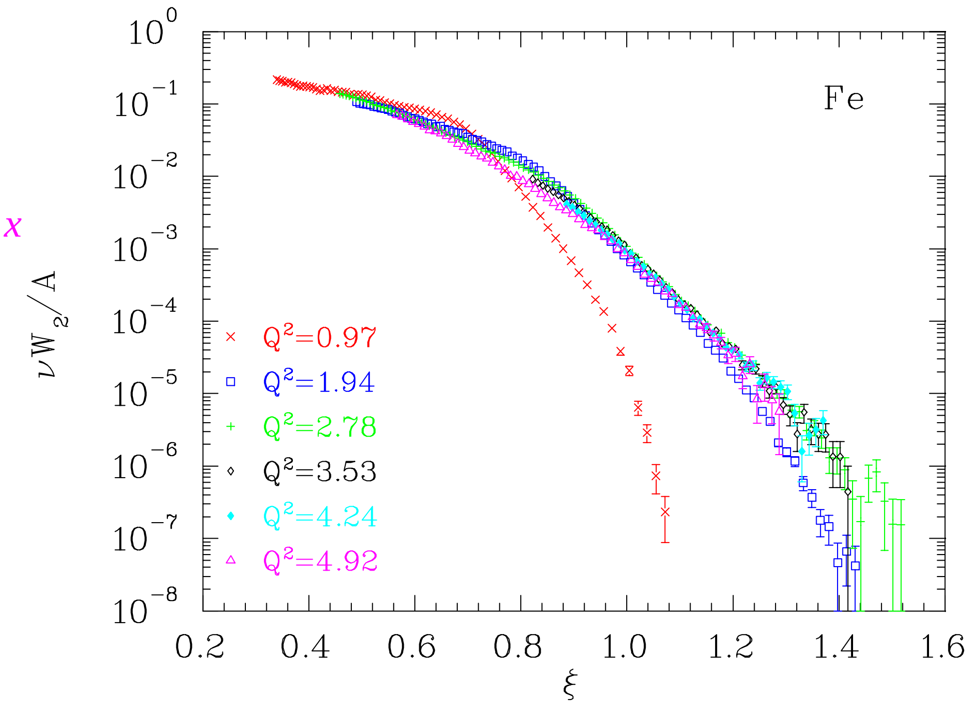
$$\xi = \frac{2x}{1 + \sqrt{1 + 4M_p^2 x^2/Q^2}} \longrightarrow x \quad (\text{as } Q^2 \to \infty)$$

ξ is the appropriate scaling variable

important at low Q^2 or high x

Even large QE contributions yield small scaling violations

May allow even greater x(ξ) coverage.



--> Extract the distribution of '***super-fast***' quarks

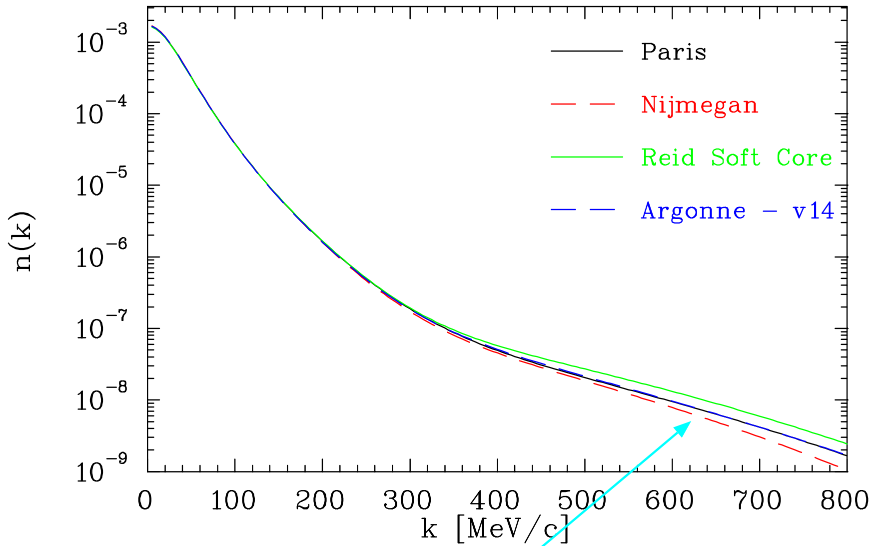
--> Determine the quark structure of high-density configurations.

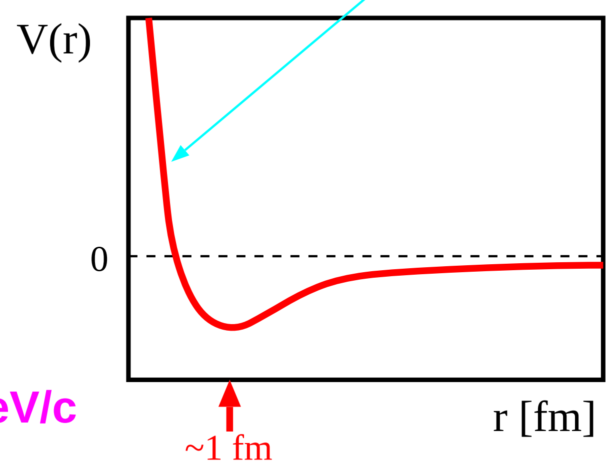
Short Range Correlations

Model of N-N interaction

Nucleon momentum distribution

With 3N interaction, these few-body calculations can be extended to A=10





These high-momentum nucleons are a small but important part of nuclear structure.

^{2}H: <10% of nucleons have k > 200 MeV/c carry >50% of kinetic energy

The high momentum components of the nuclear wave function are dominated by *short range* interactions

- These *short range correlations* (SRCs) represent high density configurations within nuclei
- Probing the high momentum nucleons allows us to select these high-density nucleon clusters

Quark distributions at x>1 and SRCs

Above x ~ 1.2 dominated by scattering from SRCs

Dotted =mean field approx.

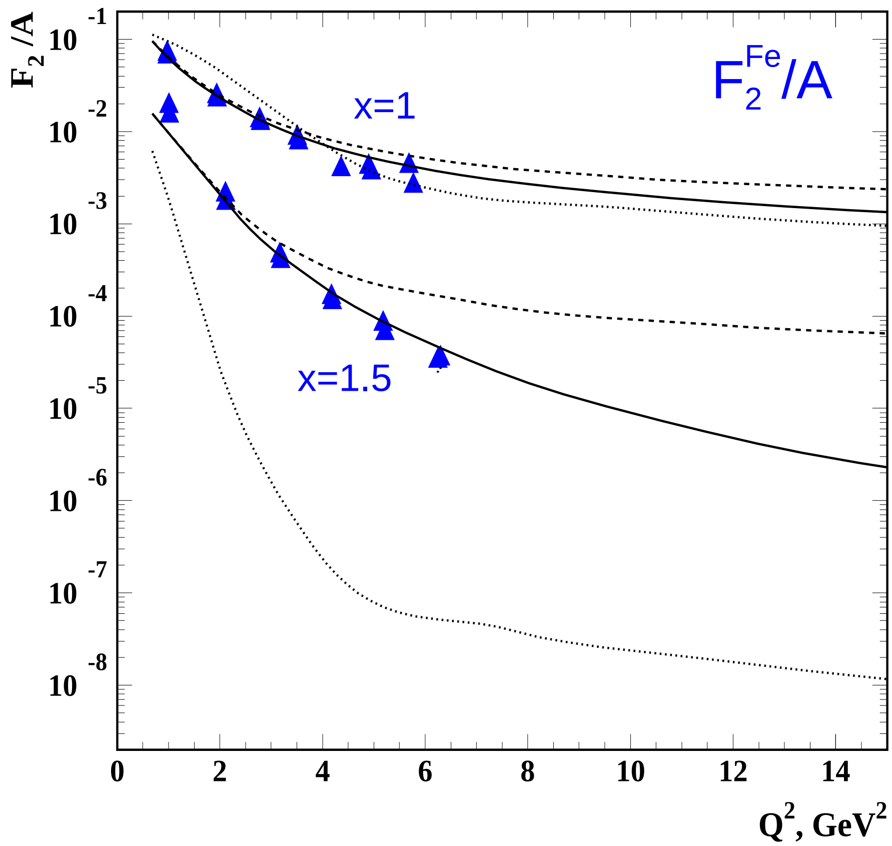
Solid = +2N SRCs.

-Frankfurt, Day, Sargsian, and Strikman, Phys. Rev. C (1993)

Dashed = +multi-nucleon.

-Frankfurt and Strikman, Phys. Lett. B94 (1980) 216

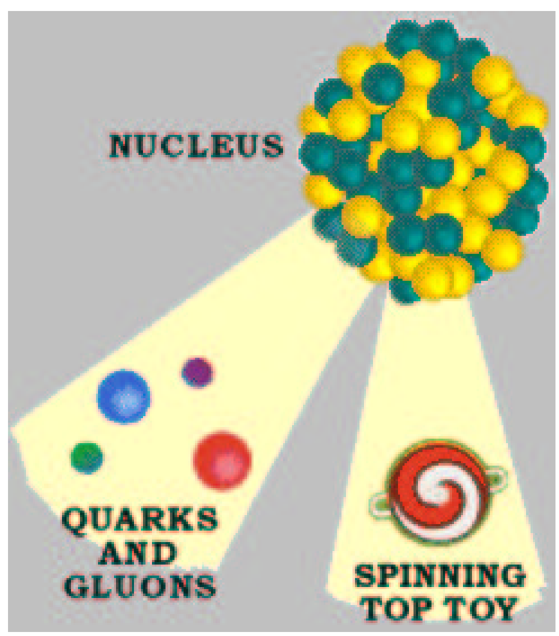
Need data on light nuclei to allow separation of nuclear effects from 2N, 3N correlations



DIS at x>1 will provide quark distributions in SRCs

Sensitive to medium modification, quark exchange, nucleon overlap, <your favorite here>, in SRCs

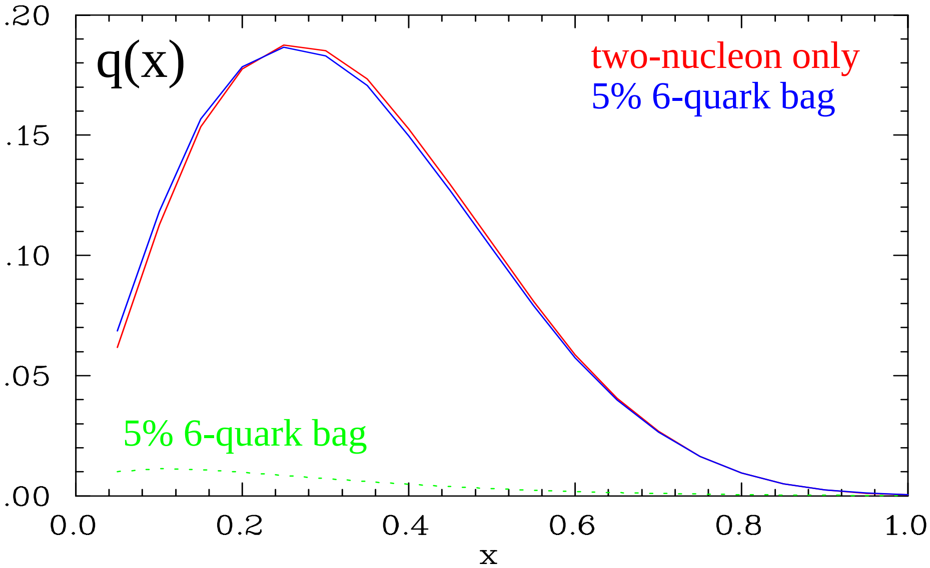
New surprises inside of the nucleus?

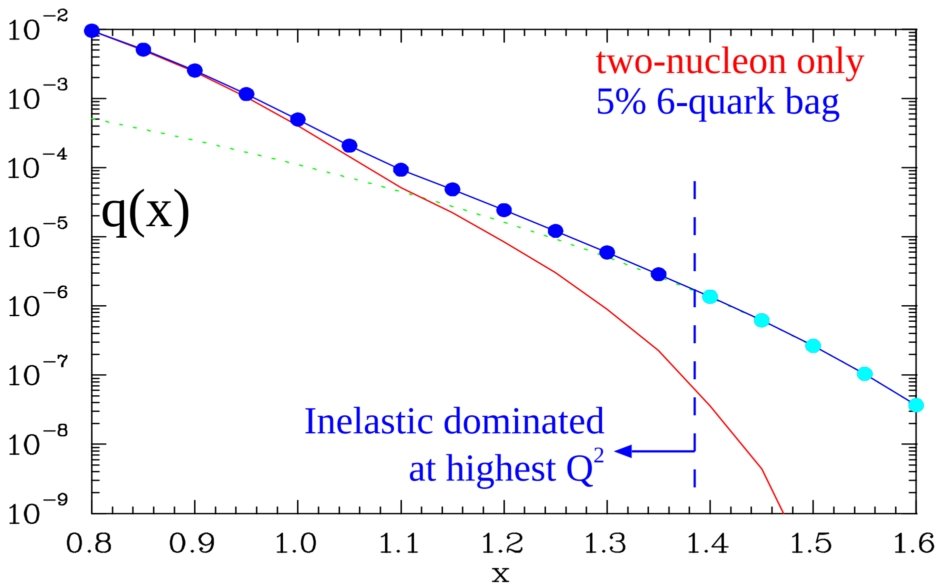


New surprises in the nucleus?

Quark distributions of high-density configurations in nuclei (SRCs)

Comparison of nucleon-only quark distributions to model with
5% admixture of 6-quark bag:





q(x) ~ x^{α} (2-x)$^{\beta}$

P. Mulders and A. W. Thomas, PRL 52, 1199(1984)

Warning:
Calculation performed by experimentalist

Such data could provide a dramatic new kind of "EMC effect"

Deuteron should provides cleanest measurement, but heavy nuclei may provide larger signal

Summary - the data to come

Additional results from compleated experiments

- A/^{3}He as x --> 3 (CLAS)
- A/D ratios as x --> 2 (Hall C: E89-008)
- new EMC ratios, $F_2(x)$ for x>1 for nuclear matter

First results from E02-019, E03-103 by September

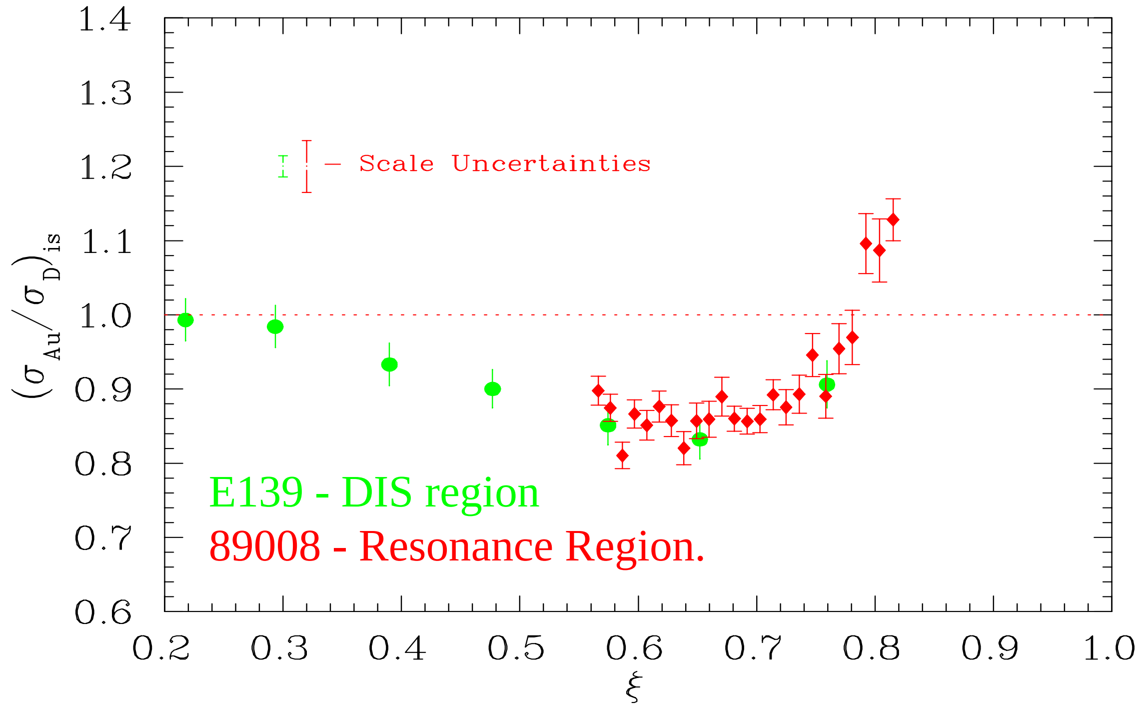
- Cross sections, ratios at ***x>1 for D, ^{3}He, ^{4}He***, and heavy nuclei (nucleon momenta exceeding 1GeV/c)
- Precise data on duality for nuclei (x<1 and x>1)
- EMC effect for ***^{3}He and ^{4}He***
- EMC effect at large x

With JLab@12GeV

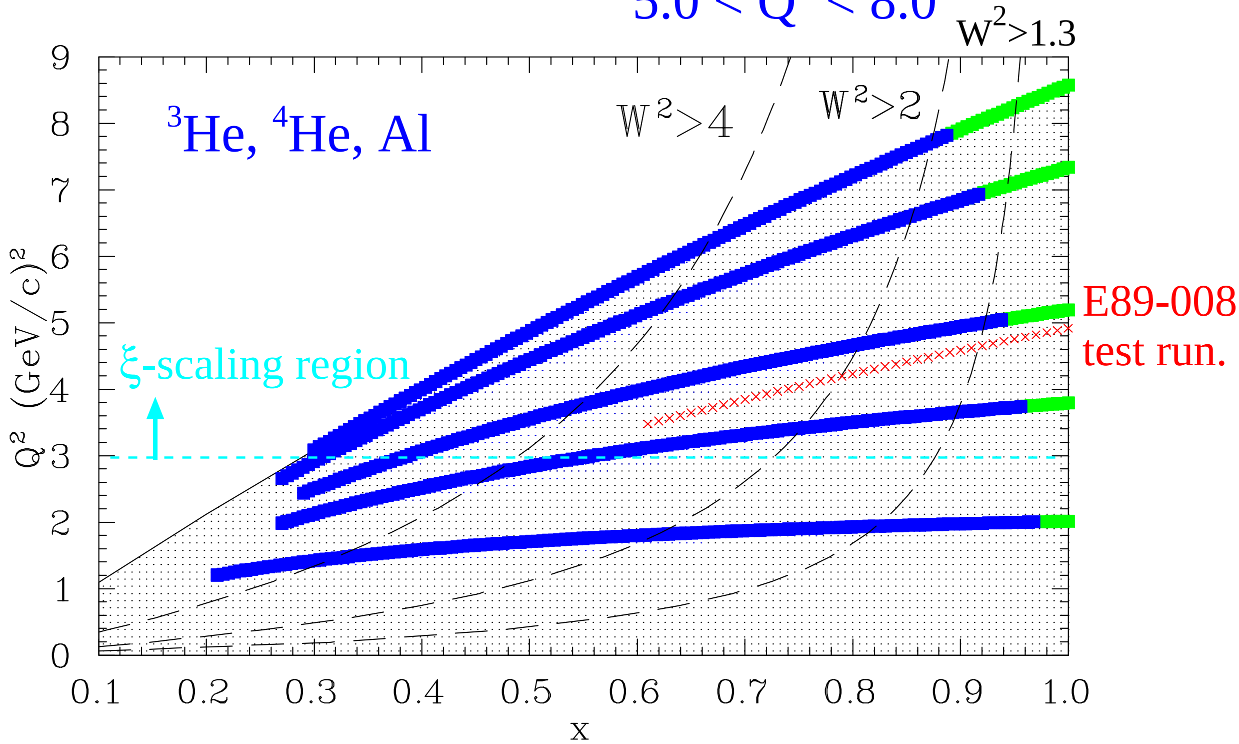
- DIS measurements at x>1 - "superfast quarks"

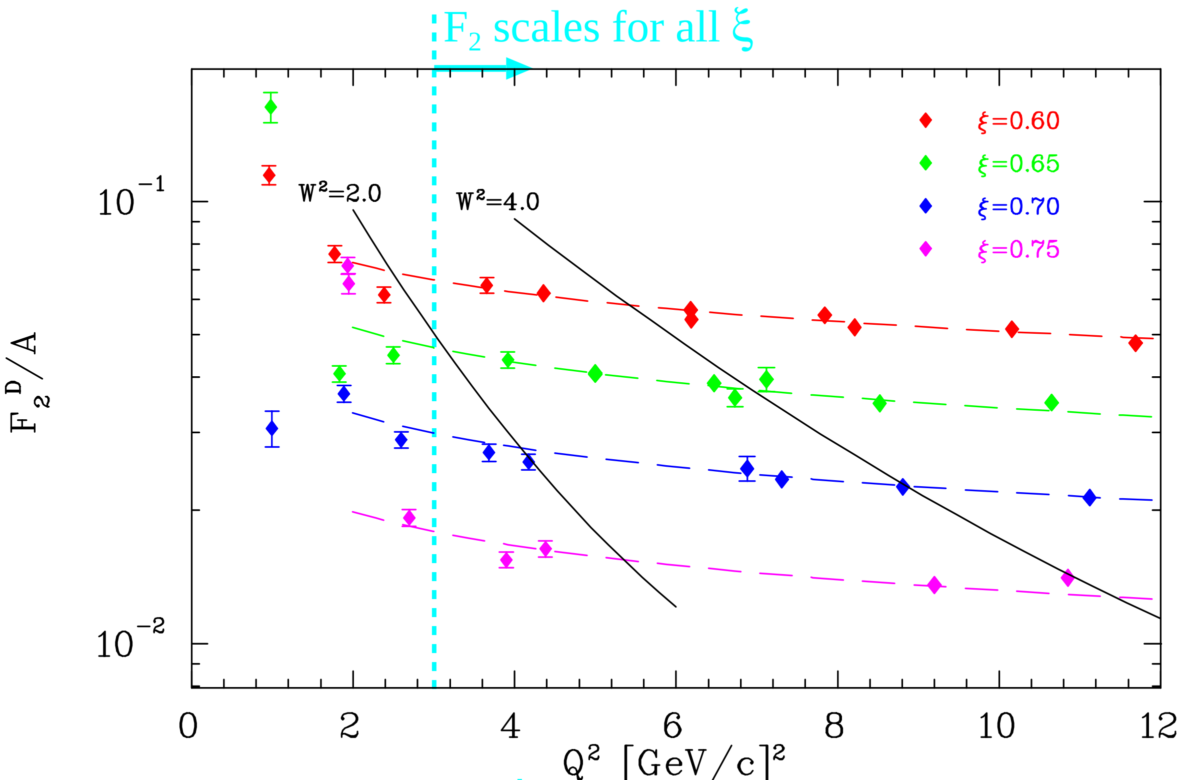
EMC Effect in the Resonance Region

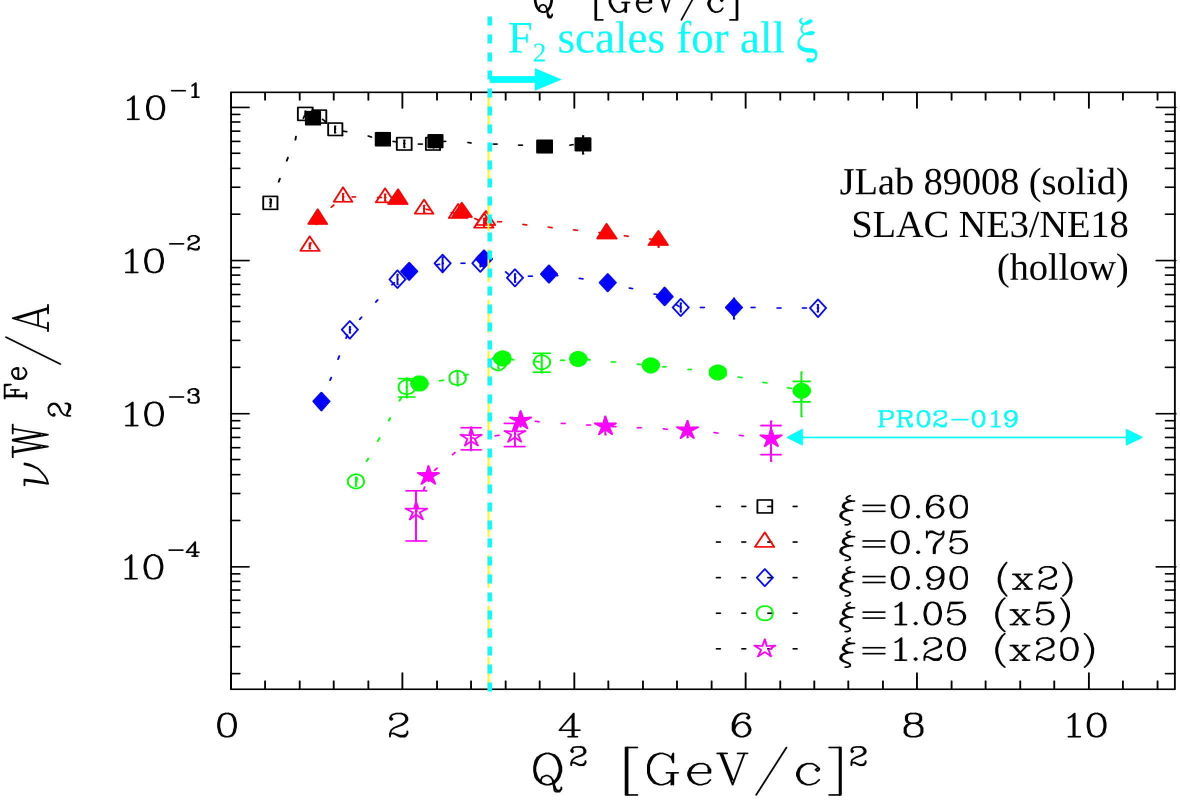
JLab 89008 results for Au/D: **1.3 < W^2 < 2.8**
Q^2 ~ 4.0



6 GeV experiment E00-101: 1.3 < W^2 < 8.0
5.0 < Q^2 < 8.0







Scaling violations

...are small for Q^2>3 GeV^2 (dominated by QE)

...decrease with Q^2 and move to higher ξ

...should cancel, at least in part, in taking the EMC ratio

y-scaling analysis - extracting $n_A(p)$

In PWIA, the inclusive cross section for QE e-A scattering is:

$$\frac{d^3\sigma}{d\Omega\, dE'} = \int (Z\sigma_{ep} + N\sigma_{en})\; S_N(E,p)\; d^3p$$

↑ Nucleon spectral function.

$$\approx 2\pi\, \bar{\sigma}_{eN} \int_{E_{min}}^{\infty} \int_{|y|}^{\infty} S_N(E,p)\; p\, dp\, dE \qquad \text{(for large } Q^2\text{)}$$

$$= \bar{\sigma}_{eN} \cdot F(y) \qquad \bar{\sigma} = \frac{E'}{2\pi Q^2} \int_0^{2\pi} (Z\sigma_{ep} + N\sigma_{en})\, d\phi$$

$$F(y) = 2p \int_{|y|}^{\infty} n(p)\; p\, dp \quad \Rightarrow \quad \boxed{n(p) = \frac{-1}{2\pi p} \frac{dF(p)}{dp}}$$

Main Assumptions:

*Quasielastic Scattering.

*Negligible Final-state interactions.

*Spectator model of the interaction (unexcited spectator):

Struck nucleon momentum, y, is determined from energy conservation (with y || q): $\nu + M_A = E_N + E_{A-1} = \sqrt{M_N^2 + (y+q)^2} + \sqrt{M_{A-1}^2 + (-y)^2}$

↑ Struck Nucleon. ↑ Unexcited (A-1) Spectator.

If the y-scaling picture is valid, σ --> F(y) --> n(p).

Is y-scaling picture is valid?

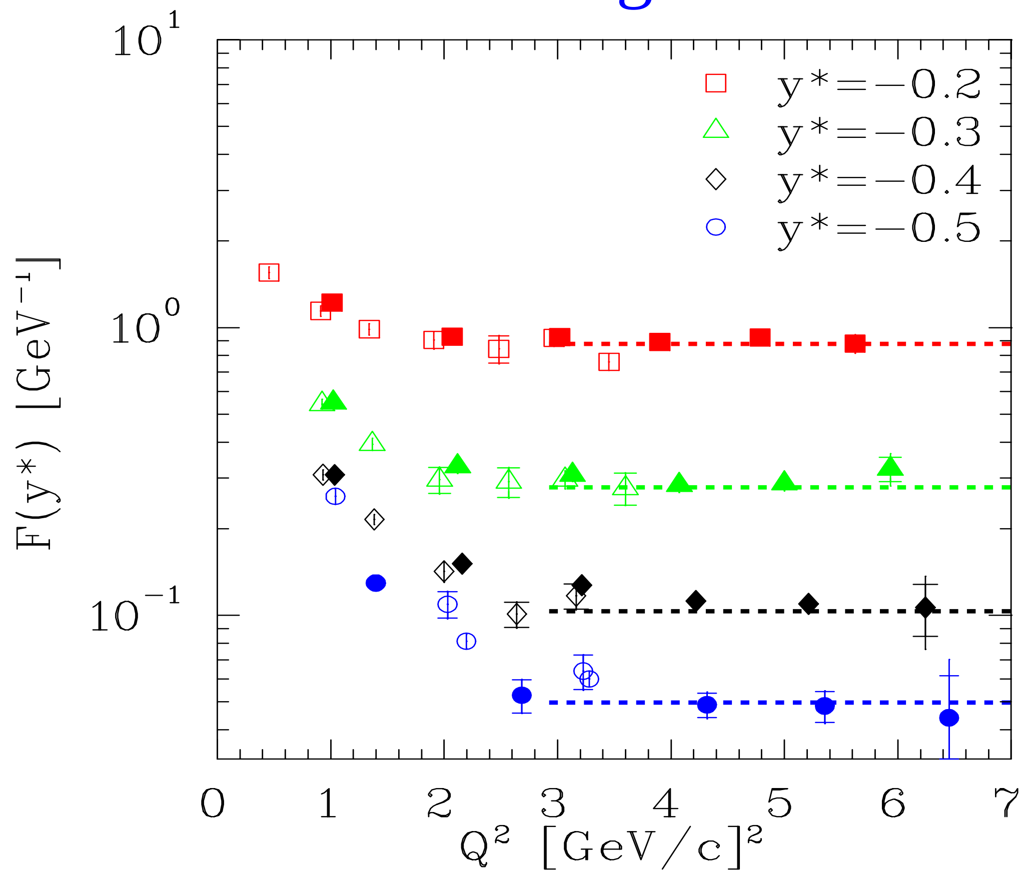
No*

* - Not for A>2.

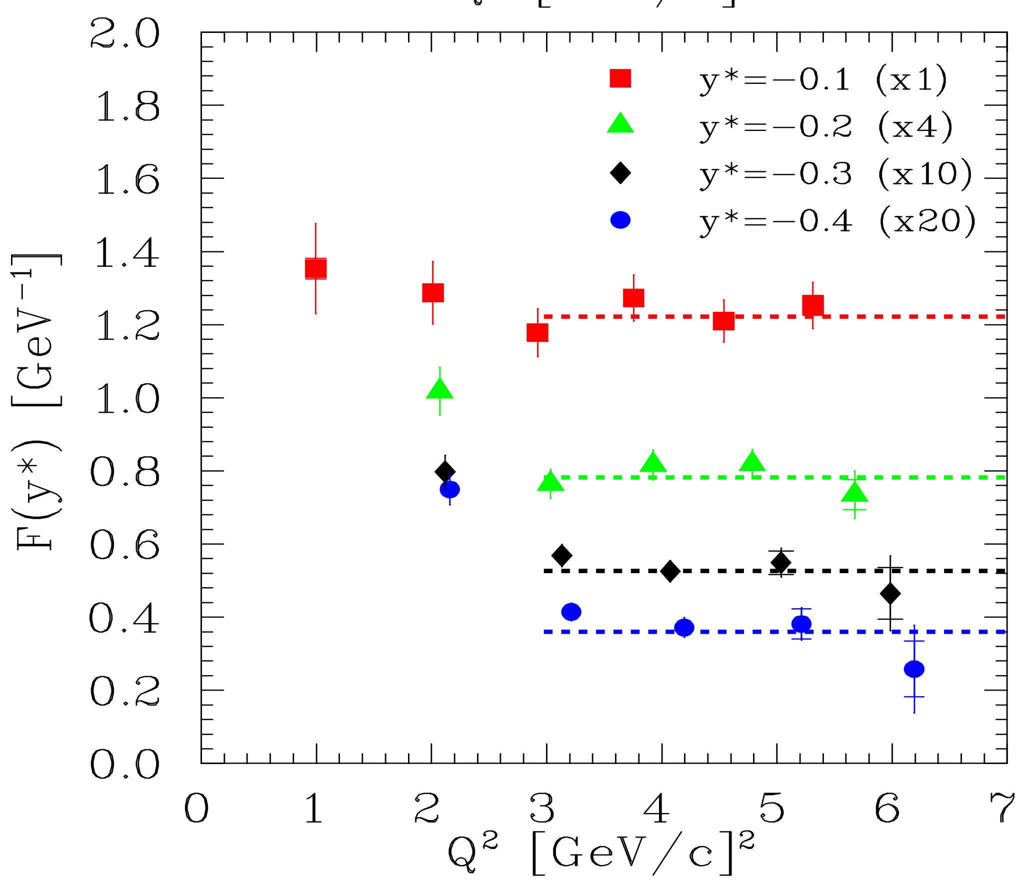
Do we observe scaling?

Iron

SLAC NE3
(open symbols)
JLab E89008
(filled symbols)



Deuterium



By $Q^2 = 3$ GeV^2, the strongly Q^2-dependent final state interactions have vanished

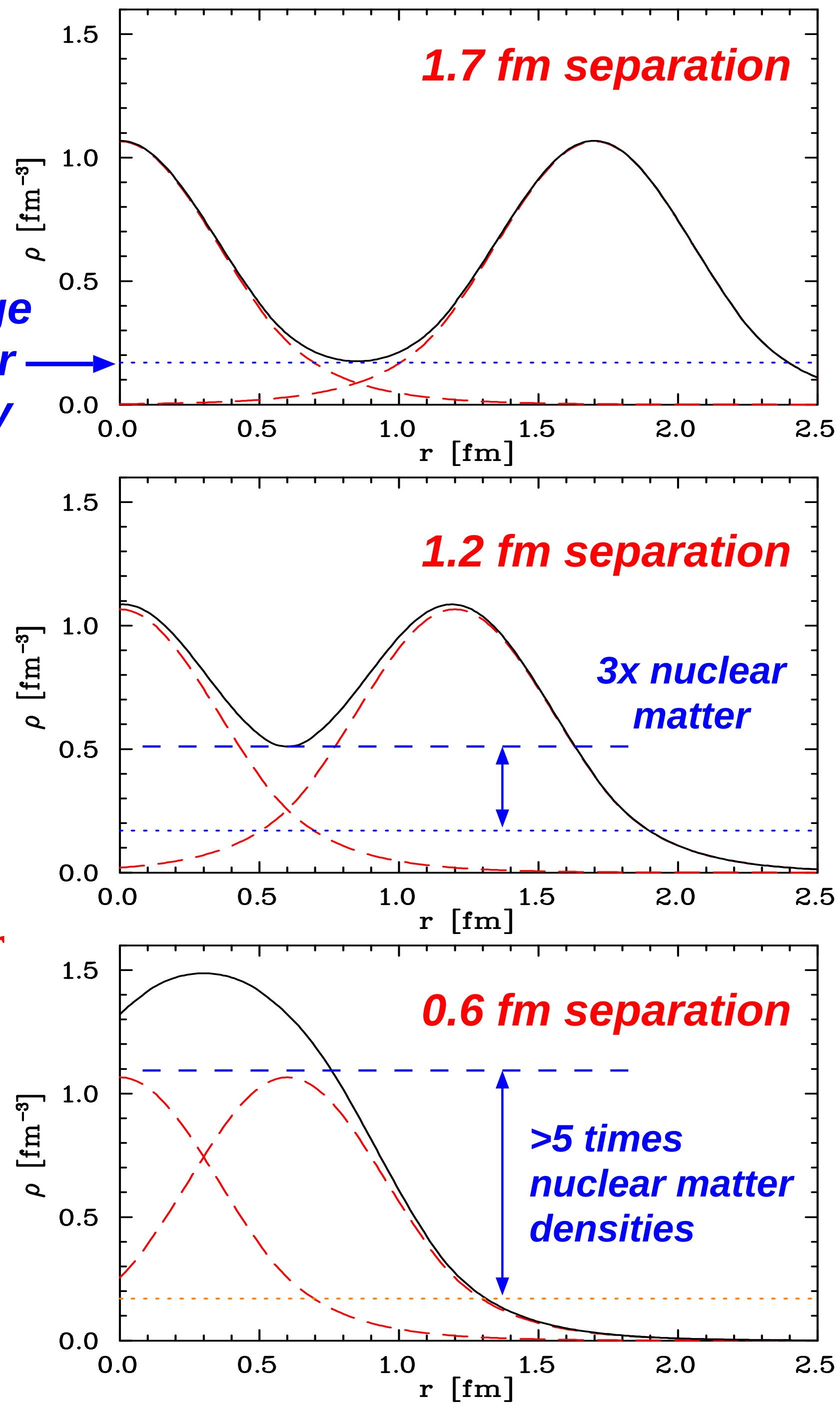
High Density Configurations

Nucleons are closely packed in nuclei

Ave. separation ~1.7 fm in heavy nuclei

Nucleon charge radius ~ 0.86 fm (d~1.7fm)

Average nuclear density



ρ(r) from J. Kelly, PRC 66, 065203 (2002)

For a 1 fm separation there is a large overlap region at 4x nuclear matter

Comparable to neutron star densities