The Transition from Quasielastic Scattering to Deep Inelastic Scattering at $x > 1$

Are we there yet?

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Electroweak Interactions With Nuclei: Superscaling And Connections Between Electron And Neutrino Scattering
ECT* Trento, Italy
October 26-30, 2009

Preamble

Inclusive electron scattering (in light of cw accelerators) can be labeled as old-fashioned but it is clear that it provides a rich, yet complicated mixture of physics that has yet to be fully exploited.

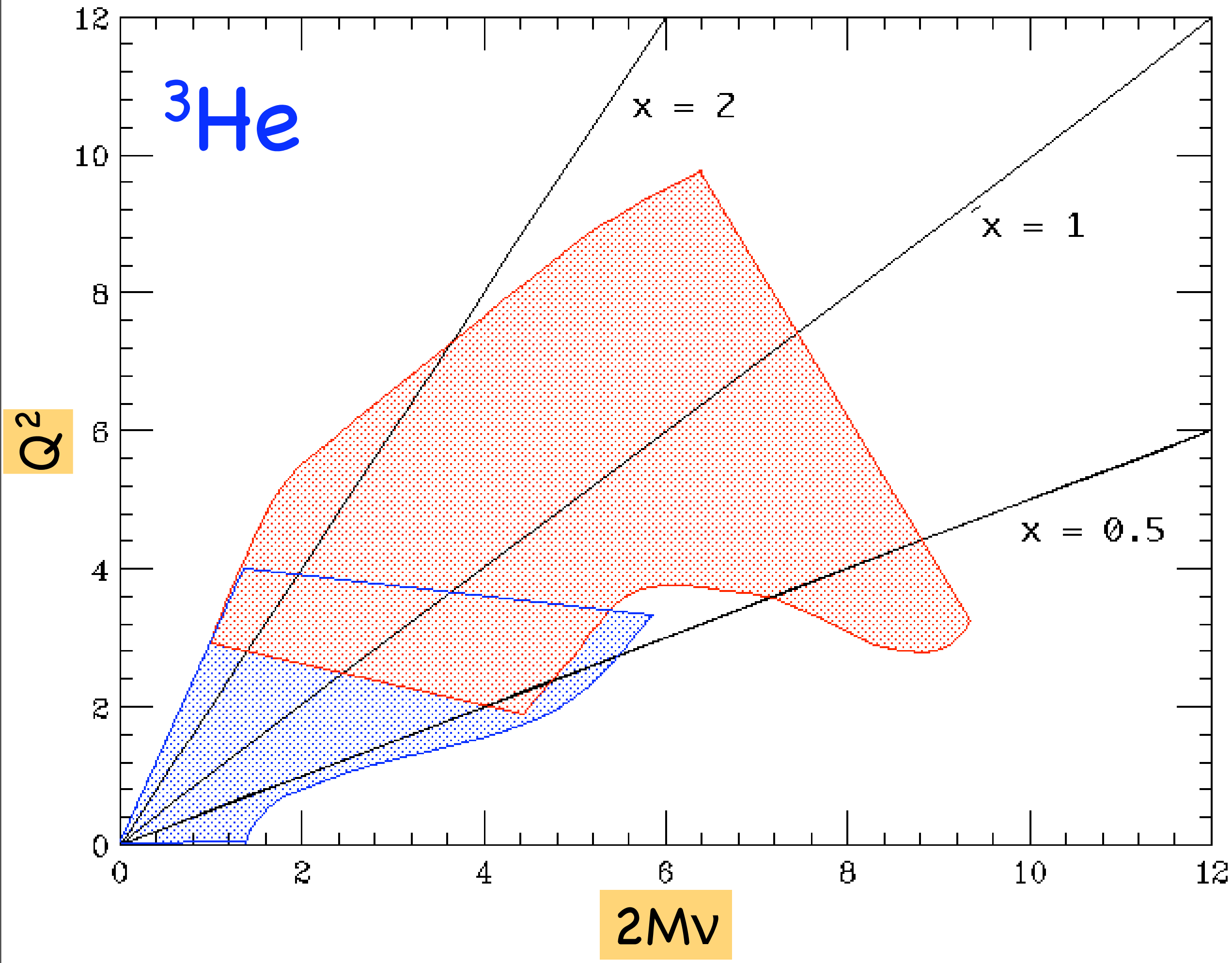
- Momentum distributions and the spectral function S(k,E).
- Short Range Correlations and Multi-Nucleon Correlations
- FSI
- Scaling (x, y, φ', x, ξ), and scale breaking
- Medium Modifications -- tests of EMC; 6-quark admixtures
- Duality
- Superfast quarks => partons that have obtained momenta $x >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

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 at every step.

New data and analysis from E02-019, Nadia Fomin, John Arrington, DD

E02-019 explored new kinematic range



NE3, E89-008, E02-019,
E-08-014, E12-06-105

- E02-019 finished in late 2004 in Hall C at Jefferson Lab. Used a beam energy of 5.77 GeV and currents up to 80uA
- Cryogenic Targets: H, ^{2}H, ^{3}He, ^{4}He
- Solid Targets: Be, C, Cu, Au
- Spectrometers: HMS and SOS
- Angles: 18, 22, 26, 32, 40, 50
- Ran concurrently with E03-103 (EMC on light nuclei)
- Nadia Fomin (UVa), Jason Seely (MIT, E03-103), Aji Daniel (Houston, E03-103)
- Analysis complete

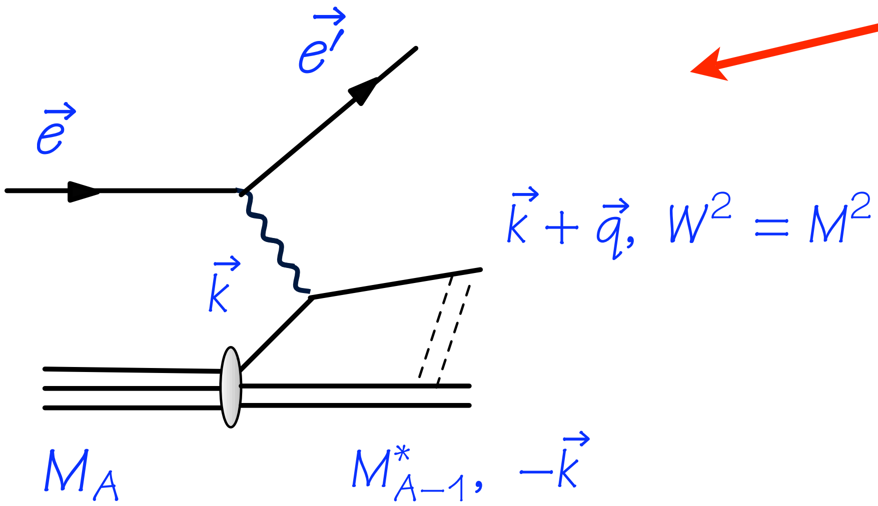
Outline

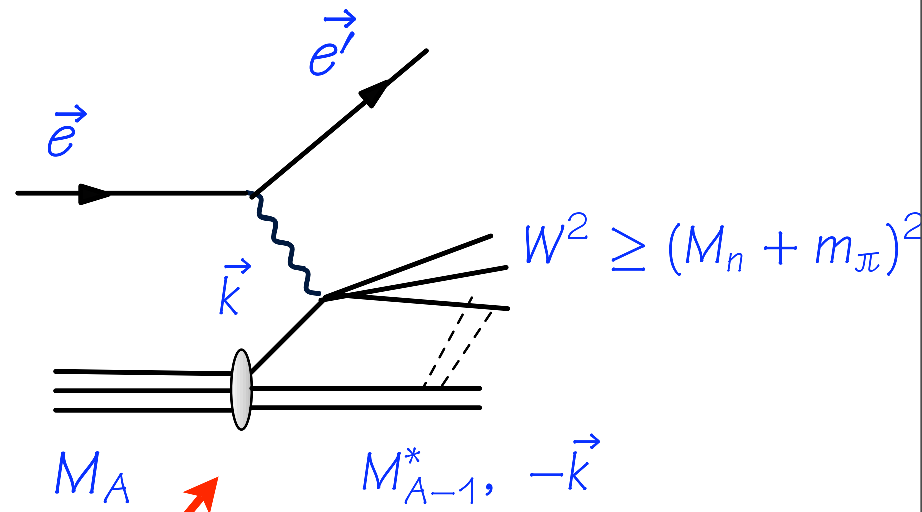
- Introduction and Basic features of e-nucleus inclusive scattering
- The Quasielastic motivation and interpretation
  - Scaling in y
  - Correlations
  - Ratios of heavy to light nuclei, in x and α_{tn}
- The transition to DIS in the Quasielastic region
  - Scaling of x, ξ
  - Duality, Target Mass corrections, evolution
- Future experiments
- Finish

Inclusive Electron Scattering from Nuclei

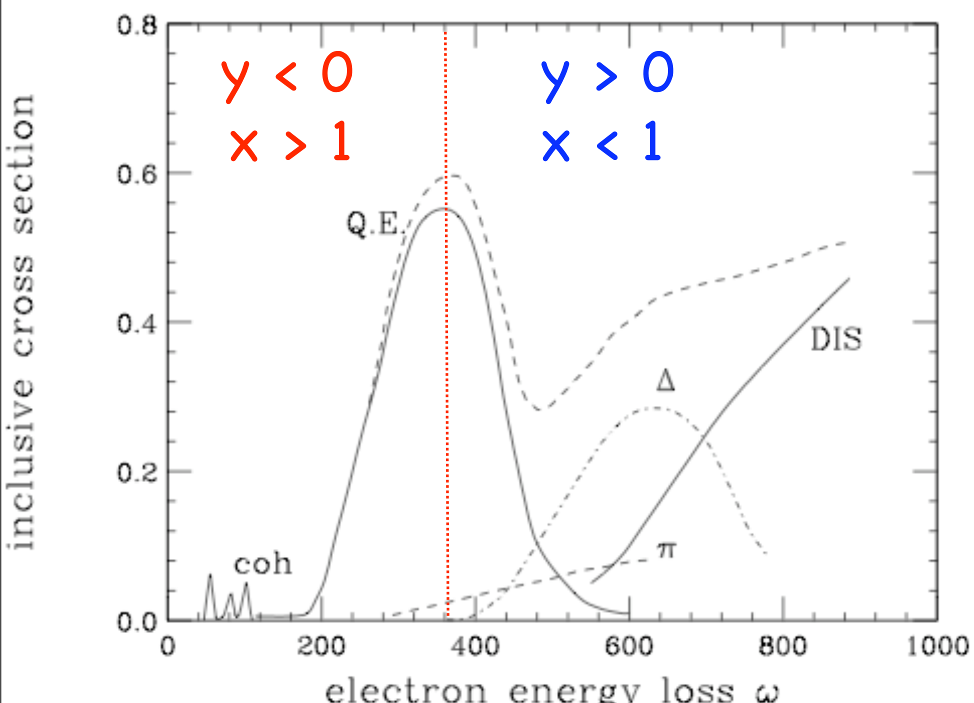
Two dominant and distinct processes

Quasielastic from the nucleons in the nucleus





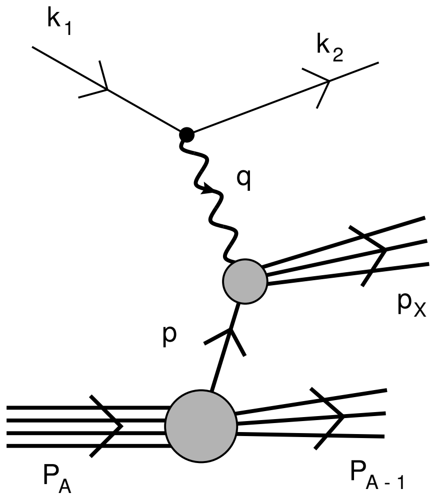
Inelastic (resonances) and DIS from the quark constituents of the nucleon.



Inclusive final state means no separation of two dominant processes

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

υ,ω=energy loss



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

The two processes share the same initial state

QES in IA

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

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

DIS

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

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

However they have very different Q^2 dependencies

$\sigma_{ei} \propto$ elastic (form factor)$^2 \approx 1/Q^4$

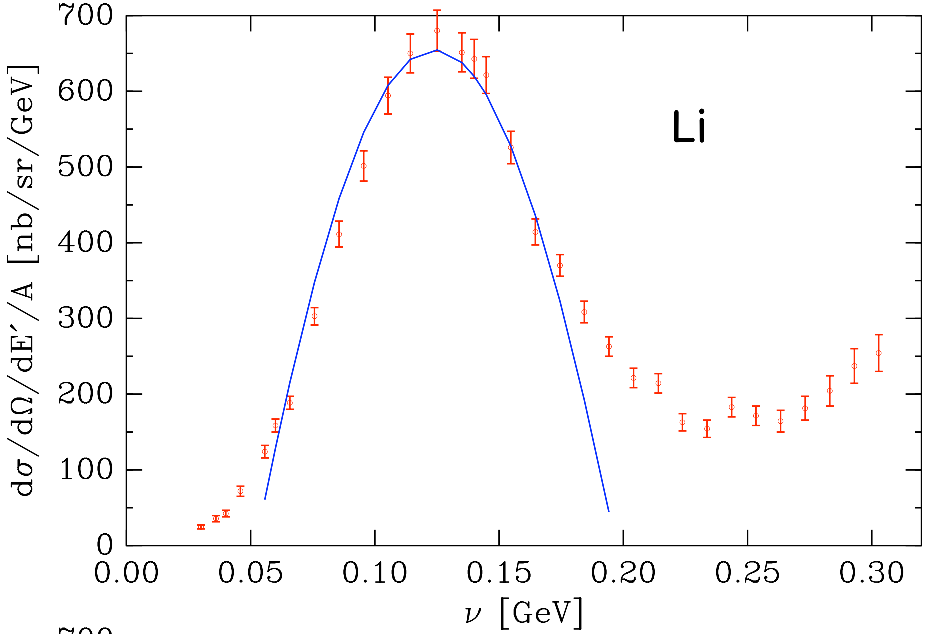
$W_{1,2}$ scale with <u>ln Q^2</u> dependence

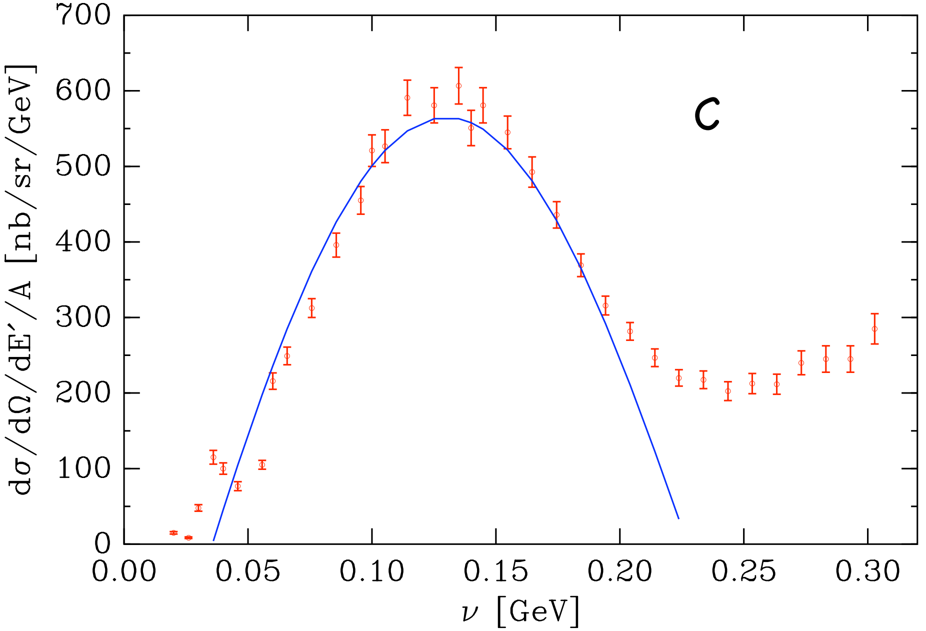
Exploit this dissimilar Q^2 dependence

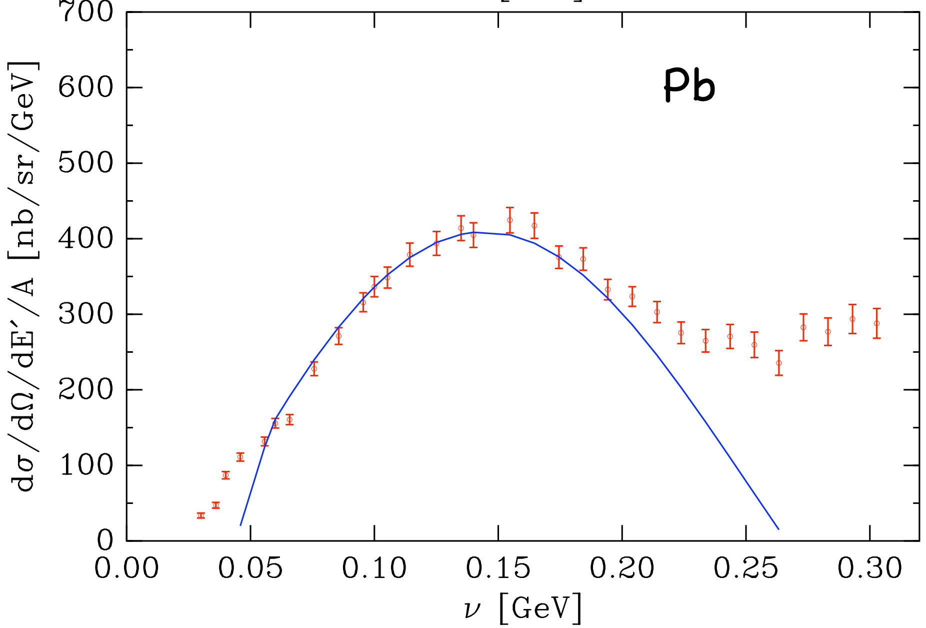
Early 1970's Quasielastic Data

500 MeV, 60 degrees

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

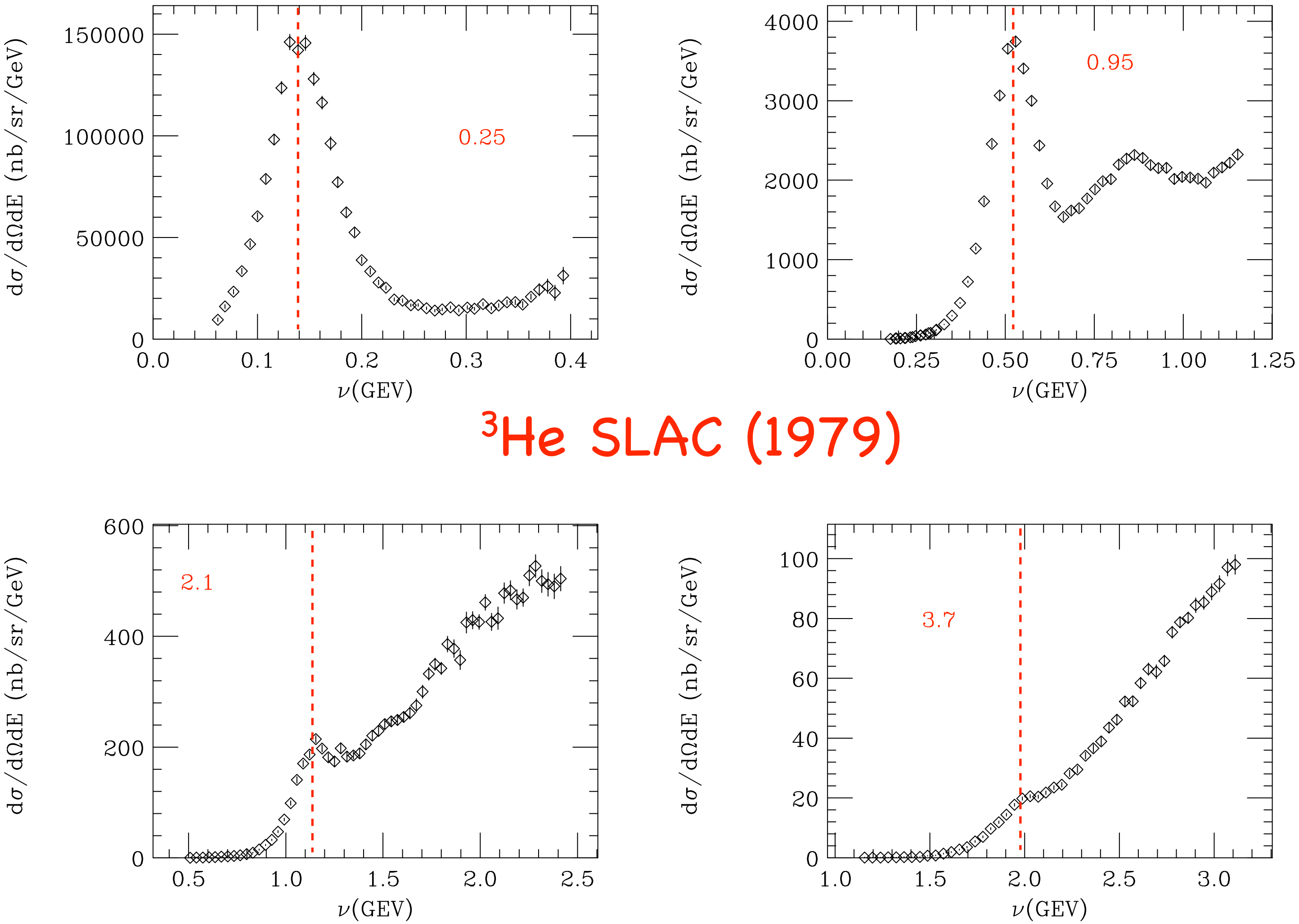






Nucleus	k_F	$\bar{\epsilon}$
^{6}Li	169	17
^{12}C	221	25
^{24}Mg	235	32
^{40}Ca	251	28
^{nat}Ni	260	36
^{89}Y	254	39
^{nat}Sn	260	42
^{181}Ta	265	42
^{208}Pb	265	44

Shape of QES Spectrum



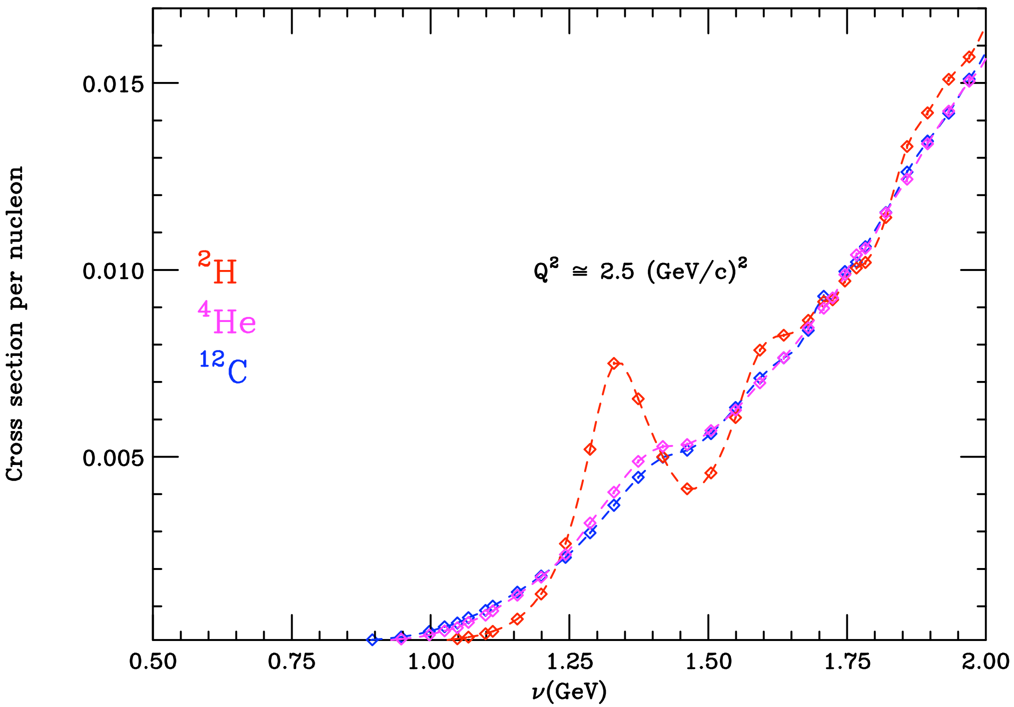
^{3}He SLAC (1979)

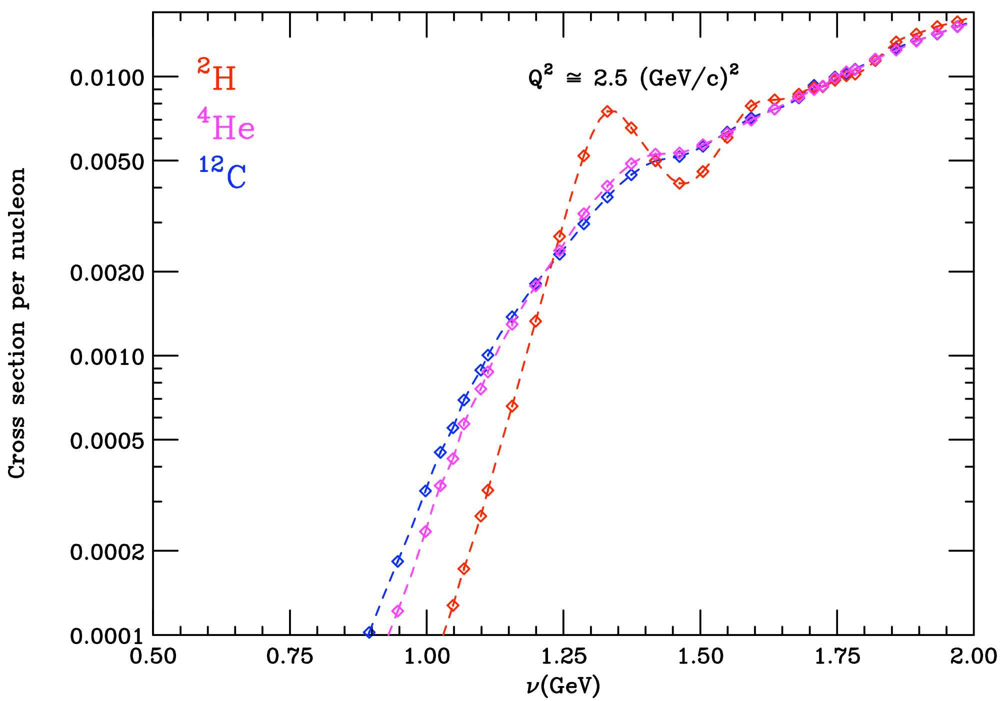
The quasielastic peak (QE) is broadened by the Fermi-motion of the struck nucleon.

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





$$\Delta\omega = \sqrt{(\vec{k_f} + \vec{q})^2 + m^2} - \sqrt{(\vec{k_f} + \vec{q})^2 + m^2}$$

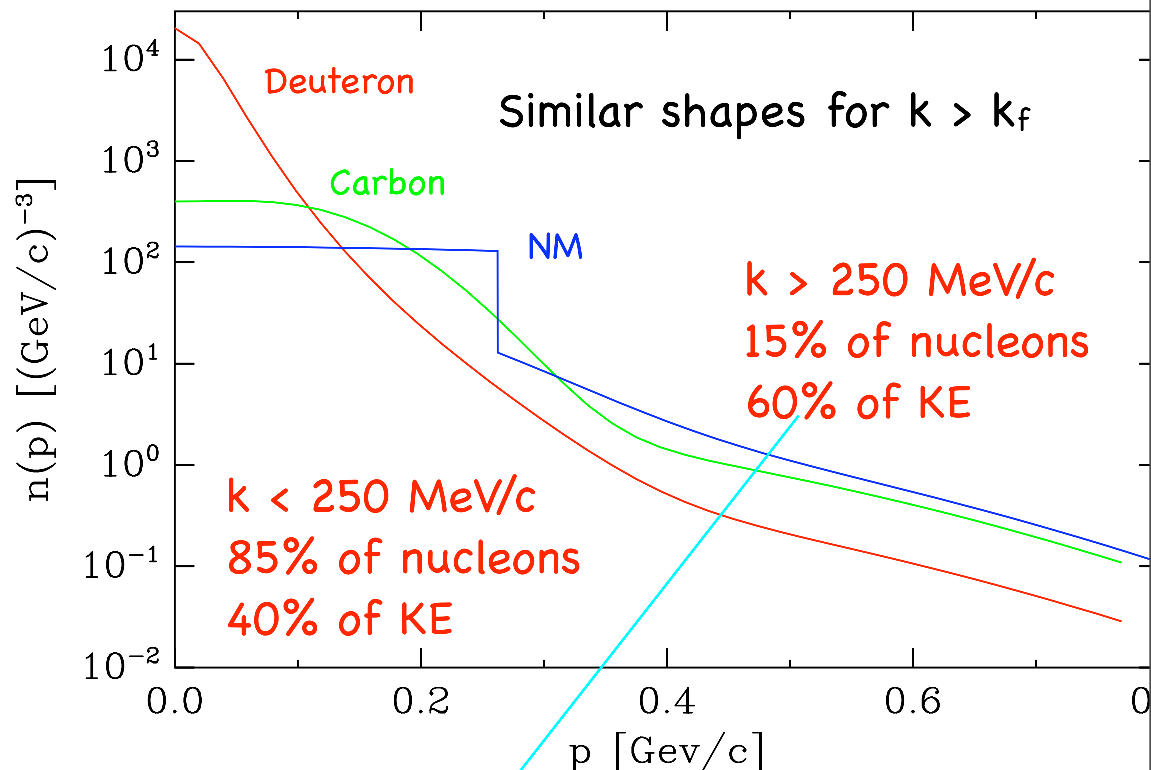
But.... plotted against x, the width gets narrower with increasing q -- momenta greater than k_f show up at smaller values of x (x > 1) as q increases

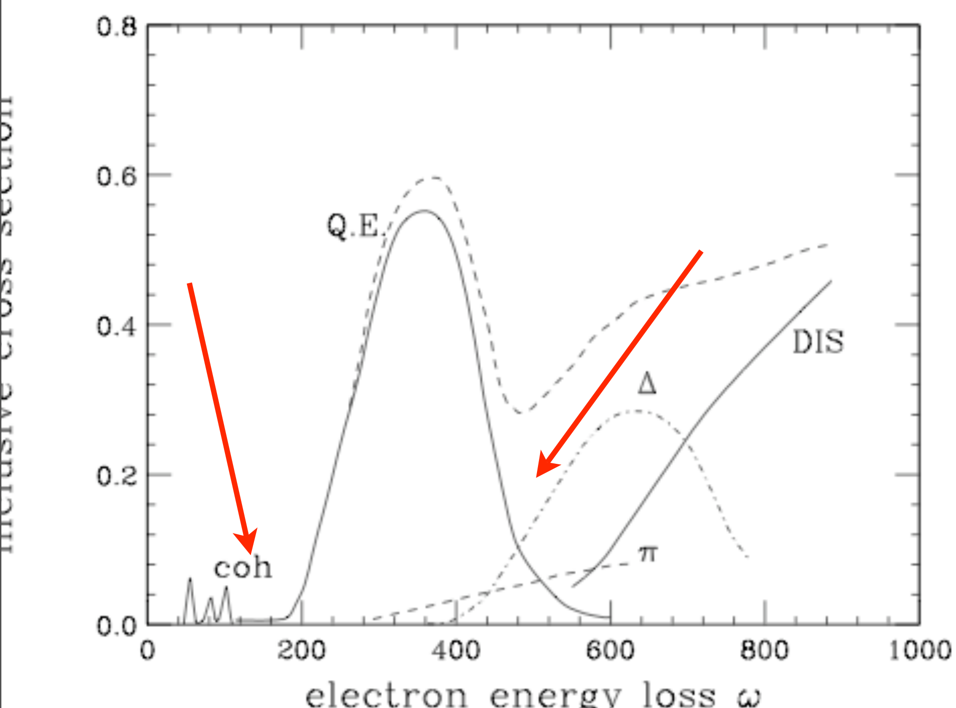
Short Range Correlations (SRCs)

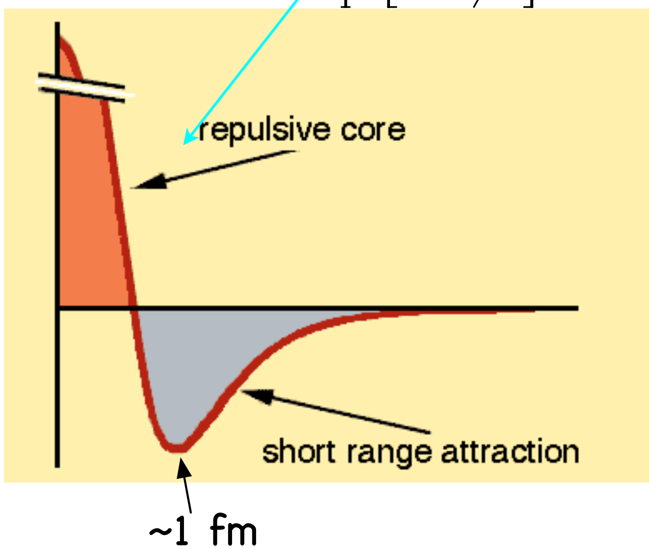
Mean field contributions: $k < k_F$ Well understood, SF Factors ≈ 0.65

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 $k > k_F$





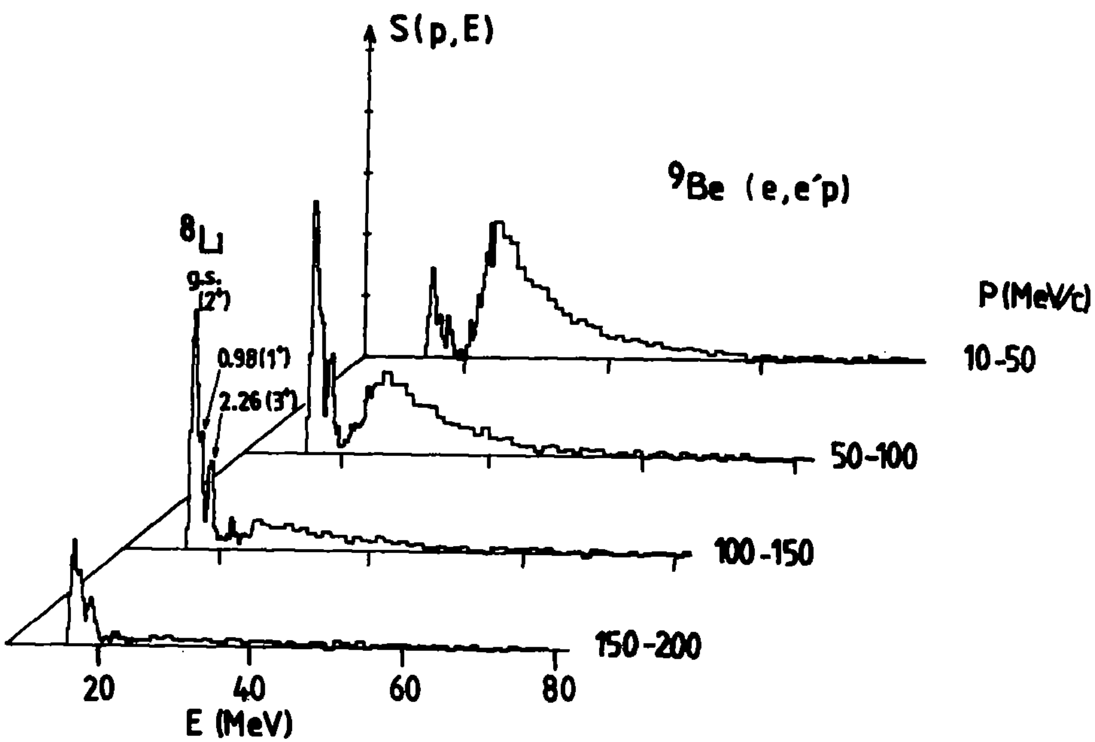


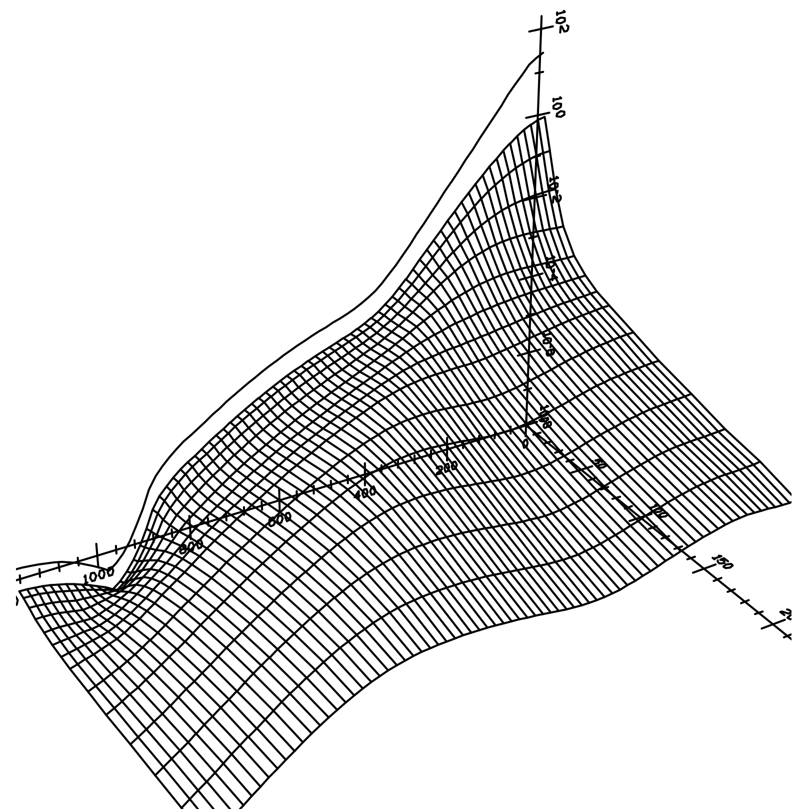
Spectral function S(E, k), not n(k) describes nuclei:

probability of finding a proton with initial momentum k and energy E in the nucleus

Experimental ^{9}Be (e,e'p)

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

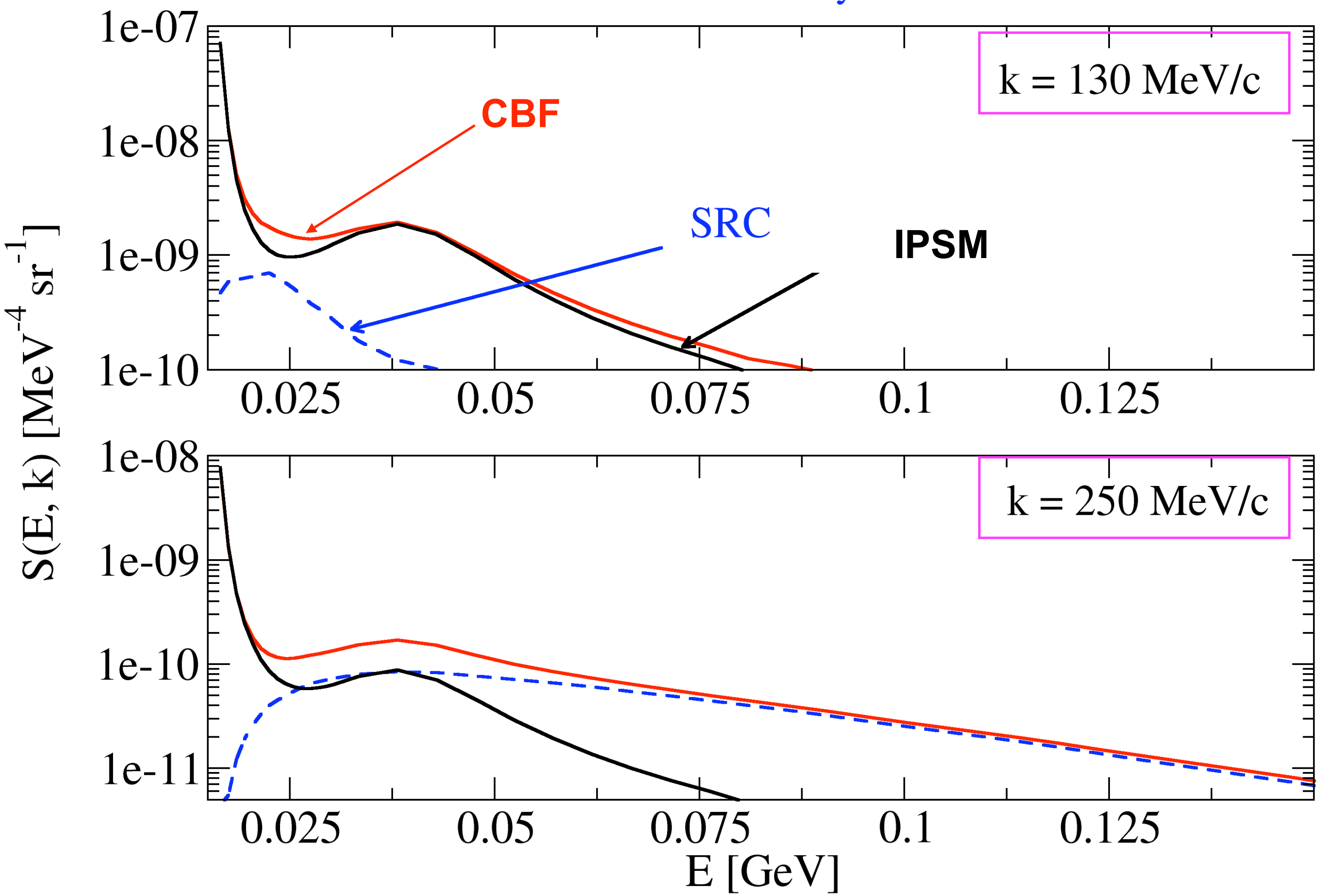




There is a correlation between momenta and separation energy: high momenta, k, are associated with large $E \approx k^2/2M$

Spectral function for ^{12}C

CBF theory



Benhar via Rohe

$\approx k_F$

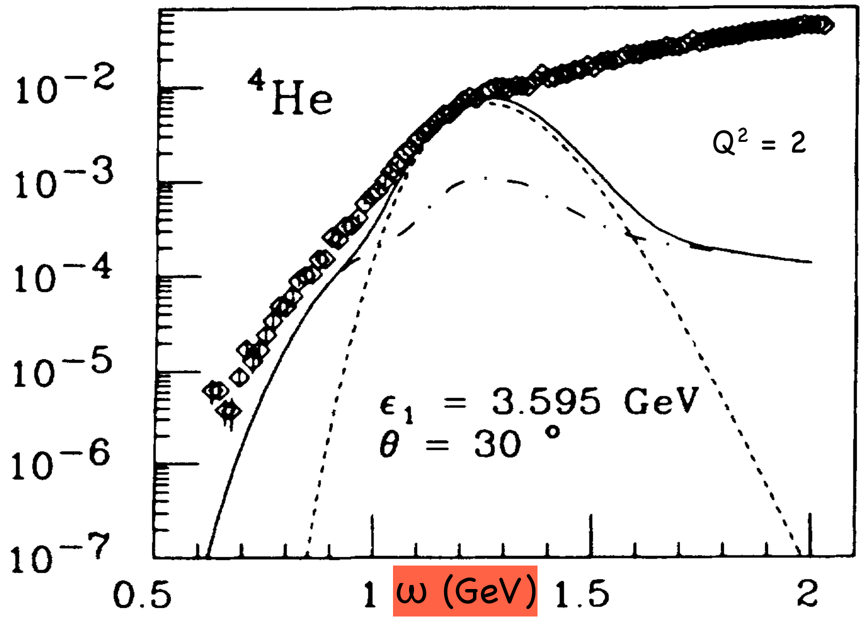
$k < k_F$: single-particle contribution dominates

$k \approx k_F$: SRC already dominates for E > 50 MeV

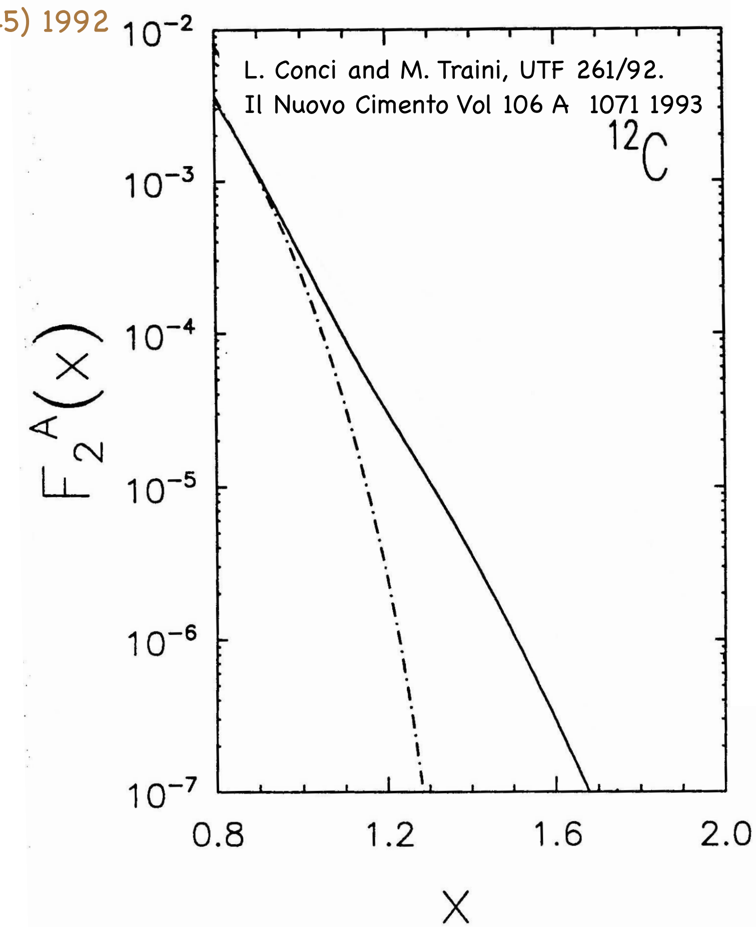
$k > k_F$: single-particle negligible

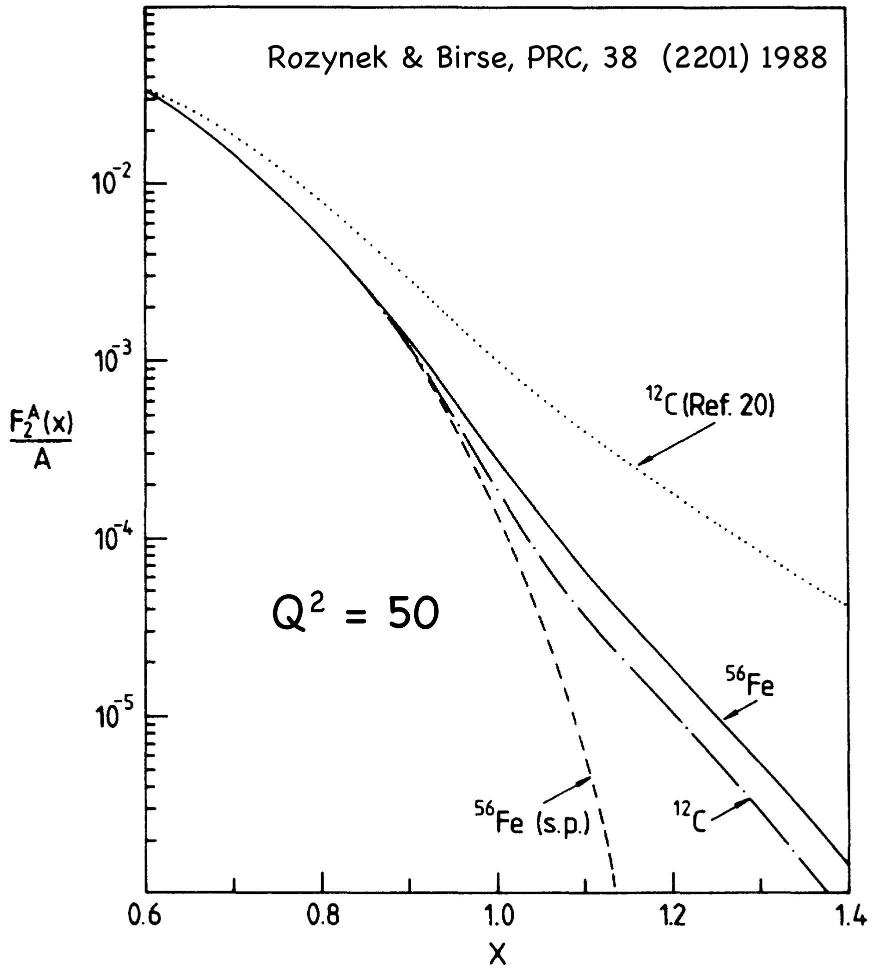
Search for SRC at high k and E in (e,e′p) and (e,e′) experiments

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



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

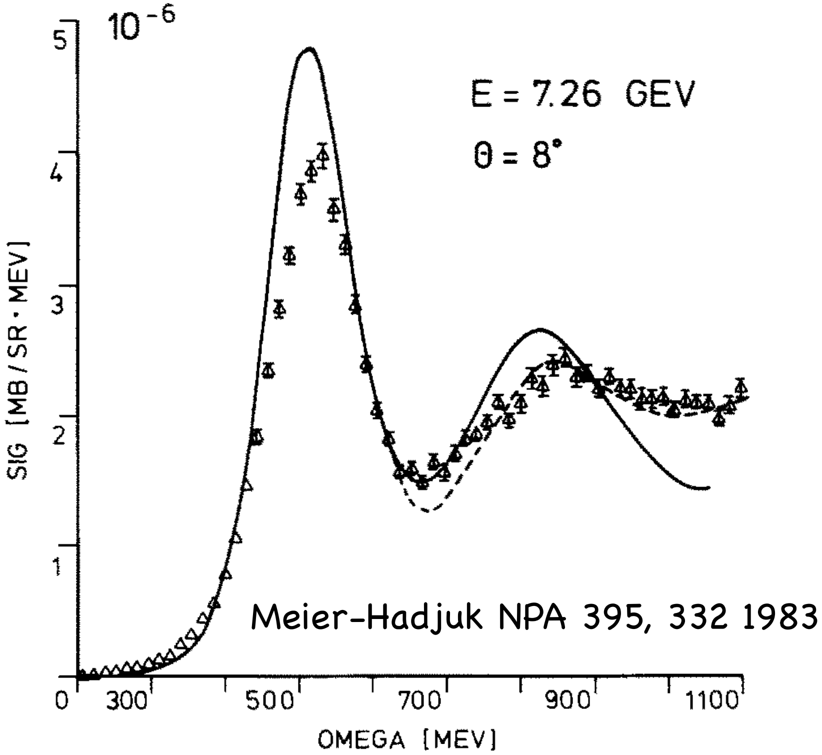


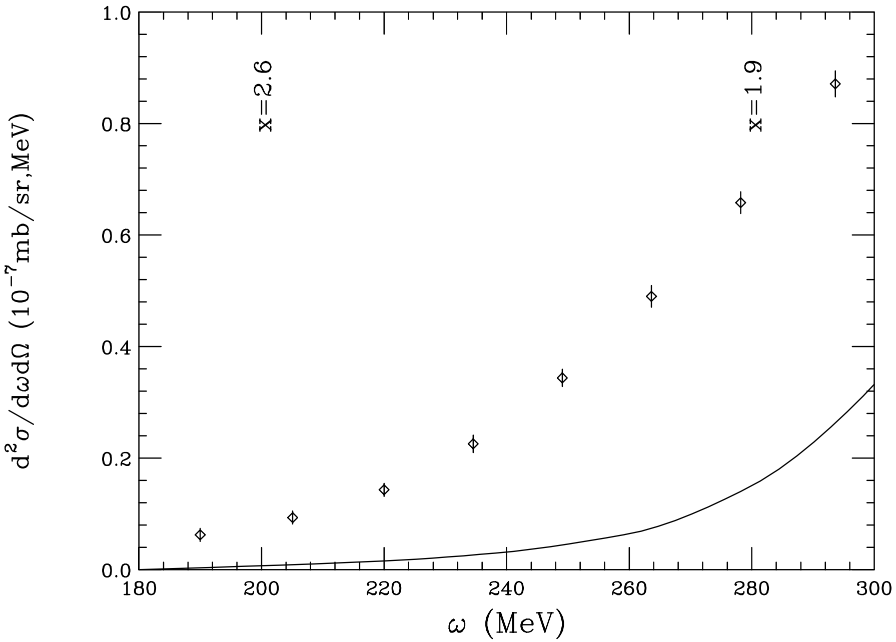


Final State Interactions

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



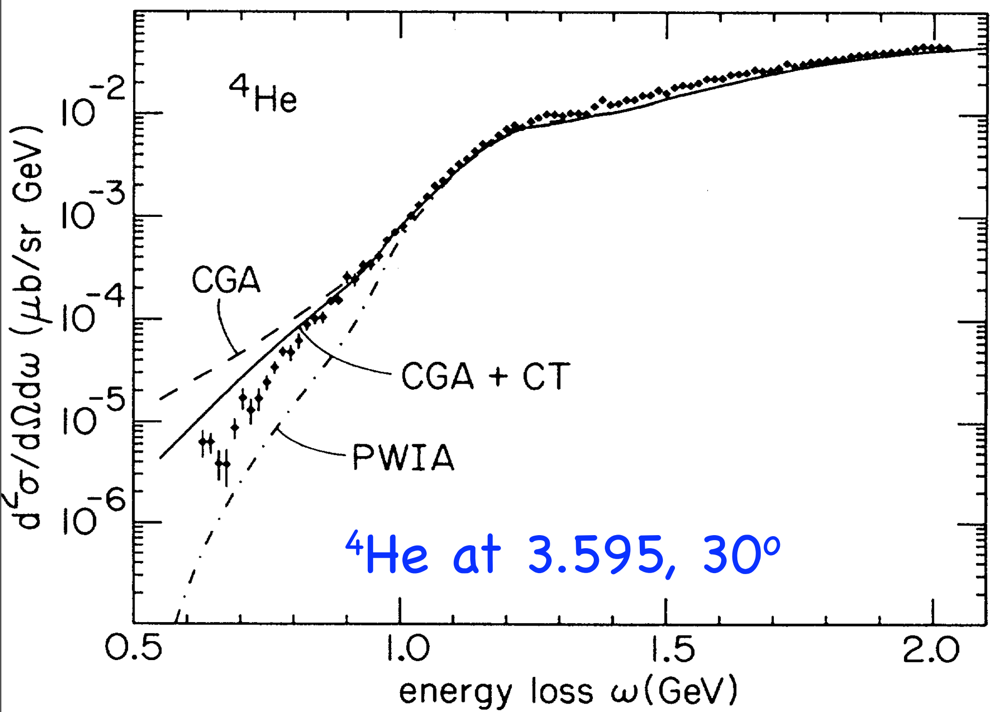


FSI has two effects: energy shift and a redistribution of strength from QEP to the tails, just where correlation effects contribute.

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

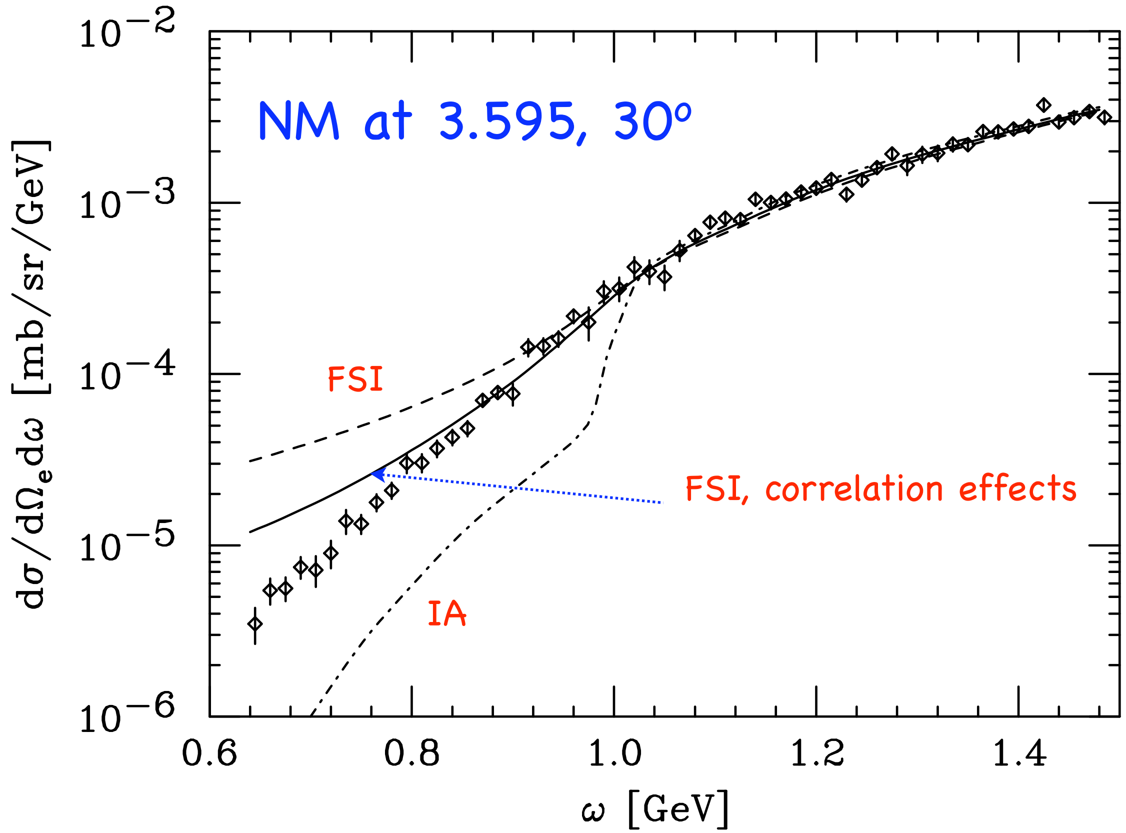
Benhar, Pandharipande, PRC 47, 2218

Benhar et al. PLB 3443, 47

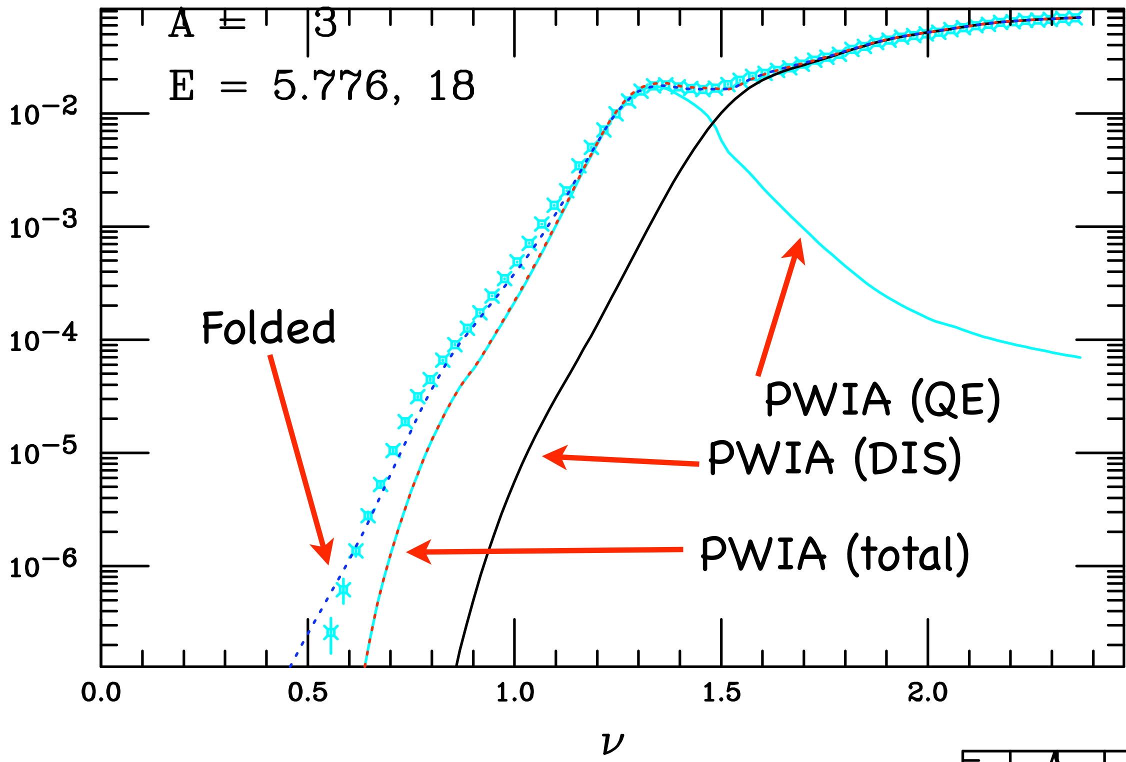
CGA over estimates the FSI

SRC suppresses FSI

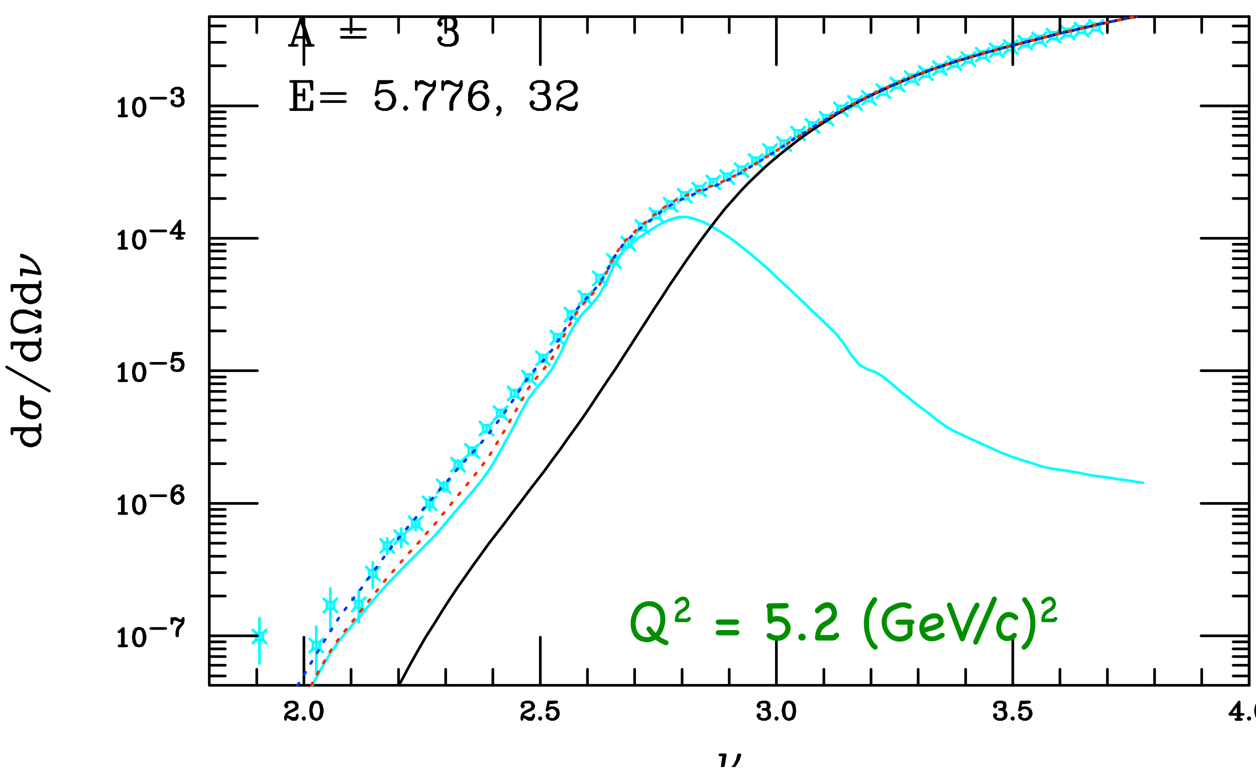
Modifications of the free space NN scattering amplitude in the medium?



^{3}He



Q^2 = 2.5 (GeV/c)^2



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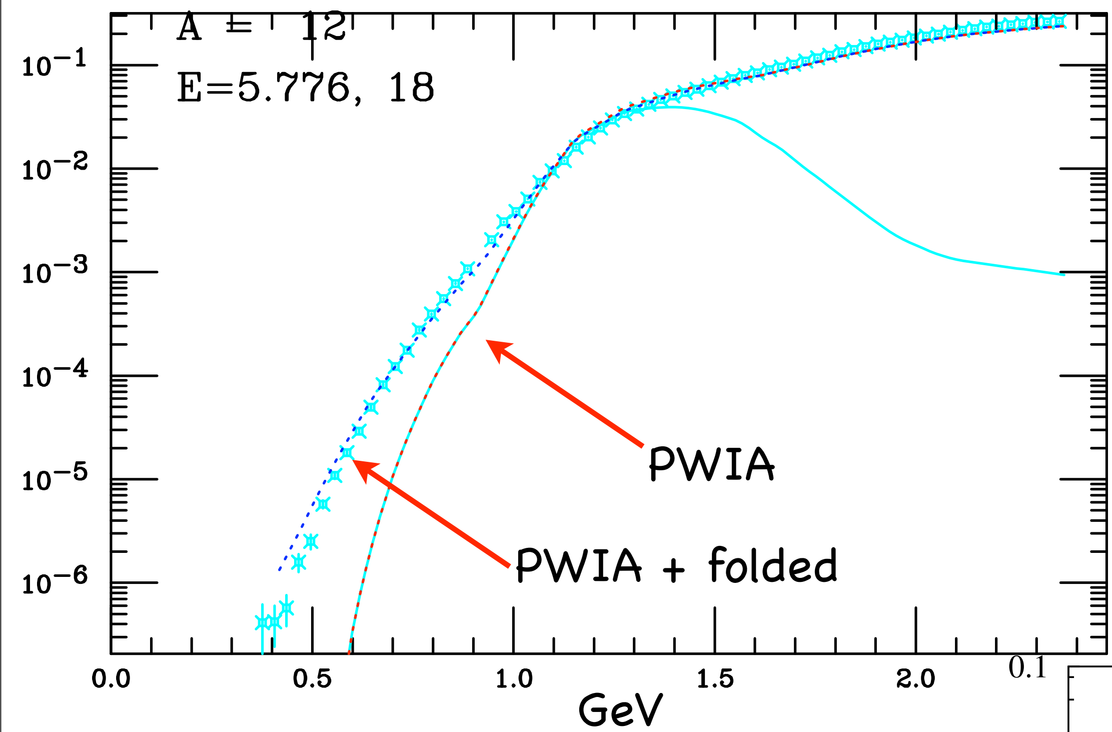
Benhar et al. PLB 3443, 47

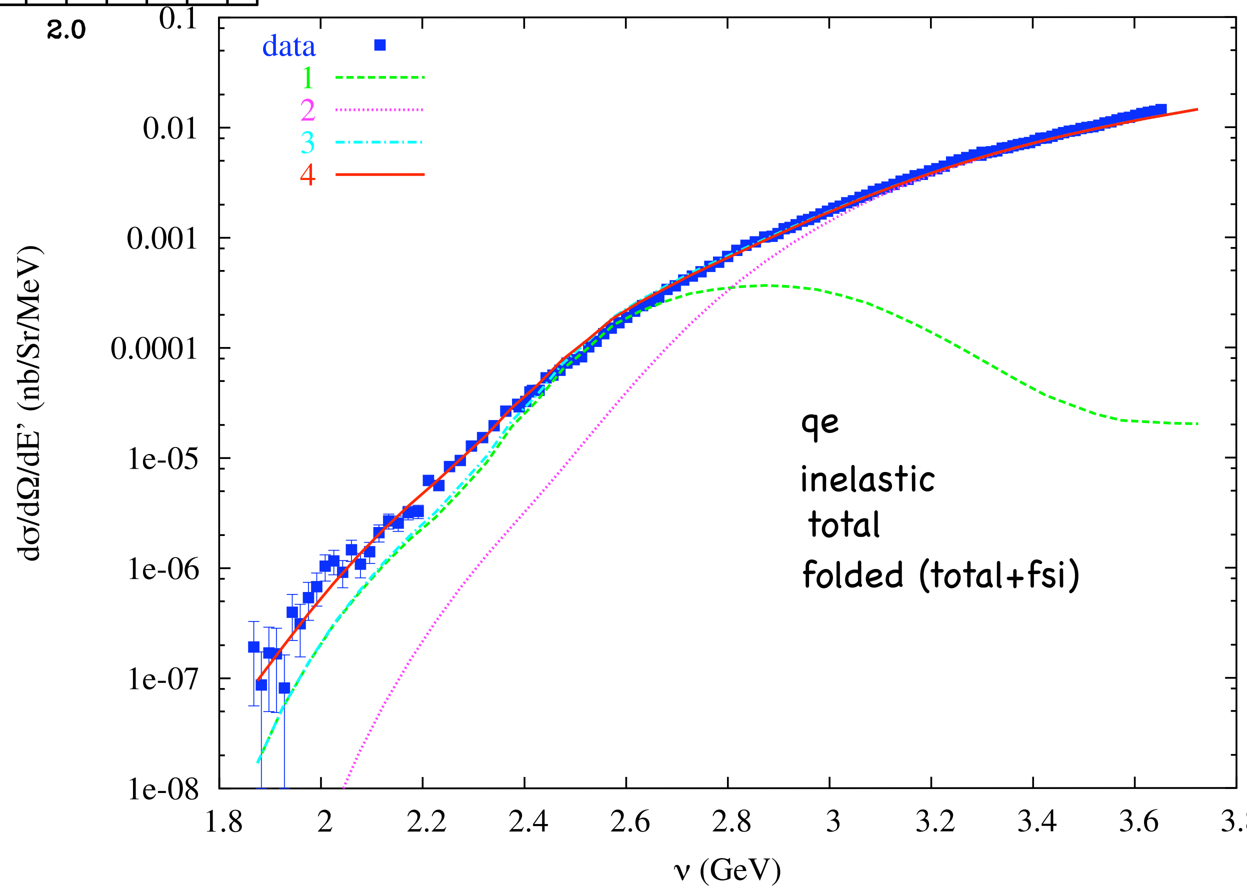
O. Benhar private comm.



O.Benhar, NMBT and CGA for FSI

Carbon 5.766, 18°,
Q^2 = 2.5 $(GeV/c)^2$

Carbon 5.766, 32°,
Q^2 = 5.2 $(GeV/c)^2$



Benhar et al. PRC 44, 2328

Benhar, Pandharipande, PRC 47, 2218

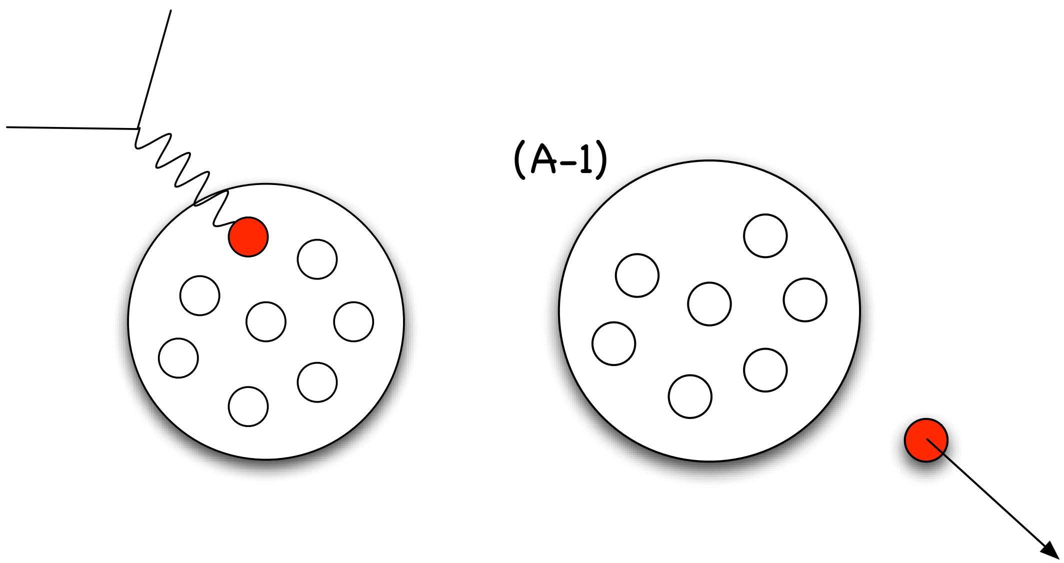
Benhar et al. PLB 3443, 47

O. Benhar private comm.

y-scaling (ν, q ⇒ y)

Single nucleon knock-out, $E = E_{min}$, A-1 system unexcited

$$\nu + M_A = \sqrt{M^2 + (p+q)^2} + \sqrt{M_{A-1}^2 + p^2}$$



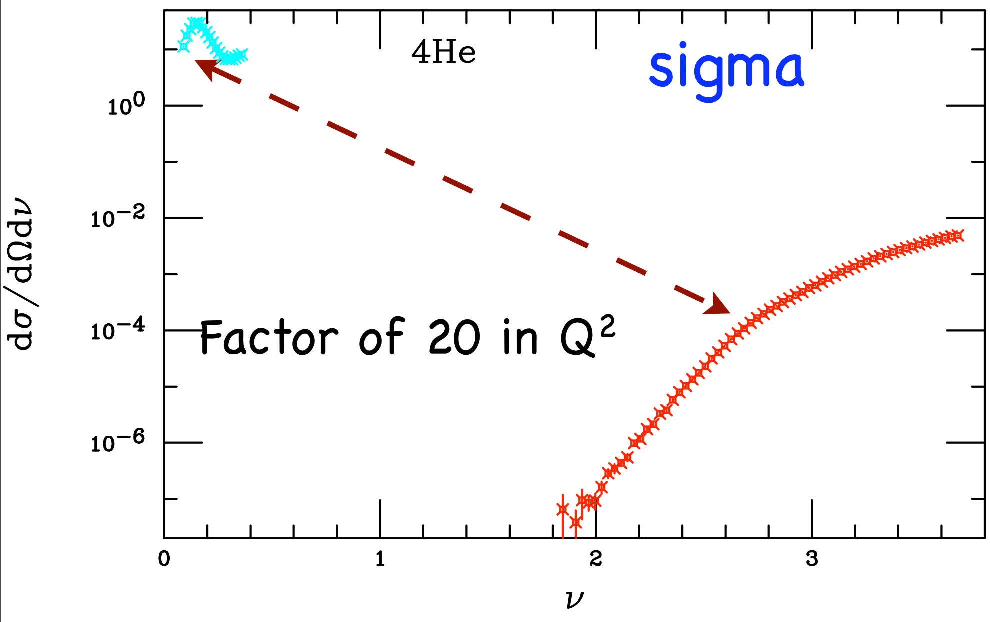
$$y \simeq \sqrt{\nu(2m_n + \nu)} - q$$

- No FSI
- No internal excitation of (A-1)
- Full strength of S(p,E) is integrated over at finite q
- No inelastic processes
- No medium modifications

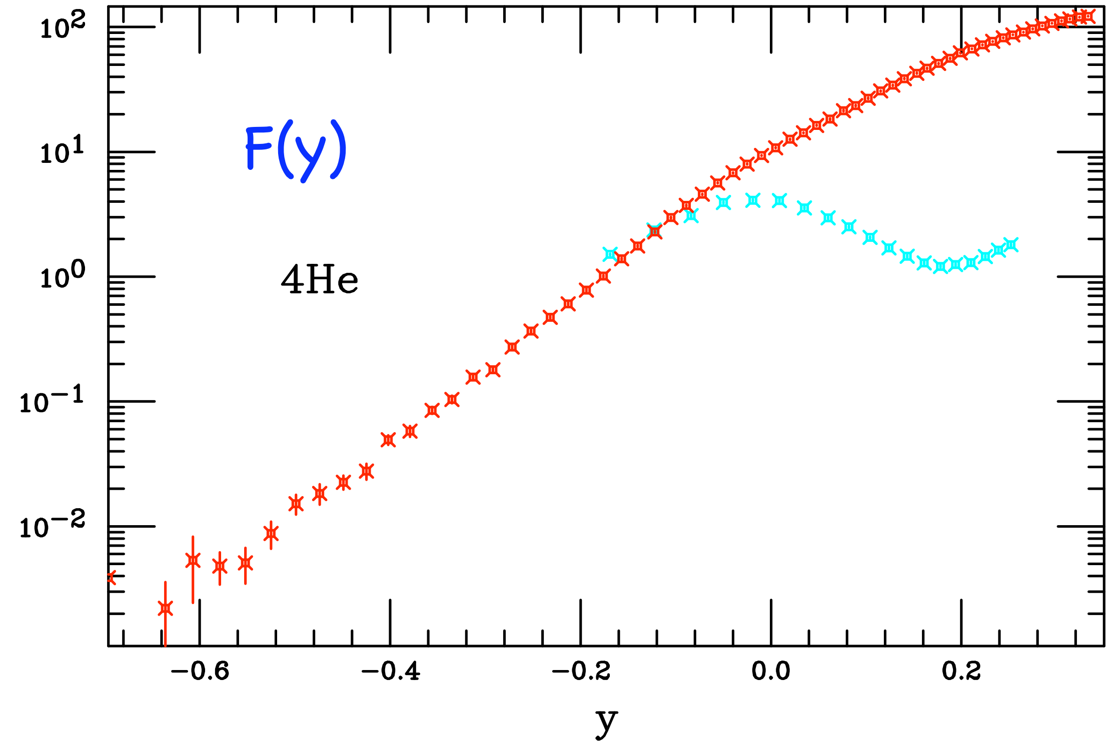
y: Momentum of knocked-out nucleon parallel to q

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

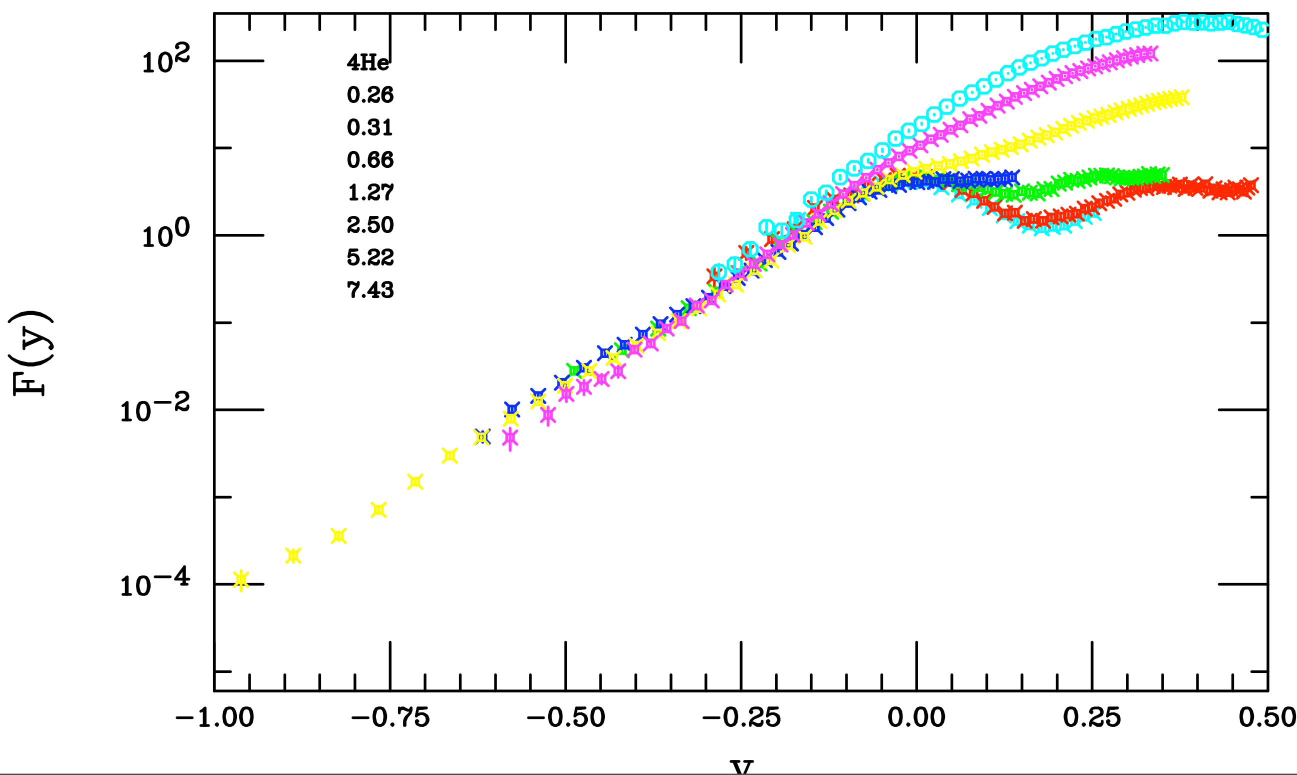
$$F(y) \equiv 2\pi \int_{|y|}^{\infty} n(p)\, p\, dp$$



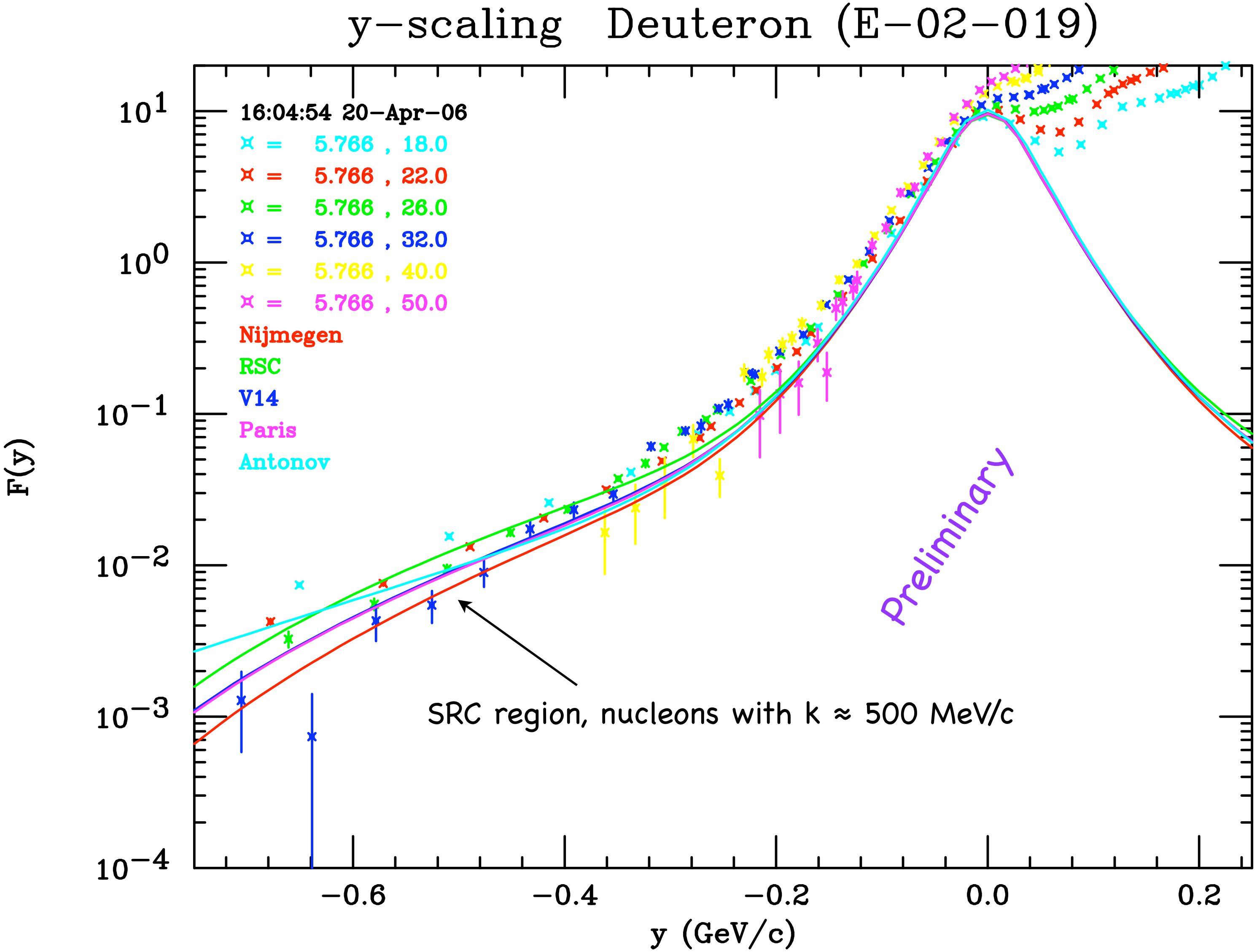
4He
sigma
Factor of 20 in Q^2
$d\sigma/d\Omega d\nu$
ν



F(y)
4He
y



4He
0.26
0.31
0.66
1.27
2.50
5.22
7.43
F(y)
y



Deuteron F(y) and calculations based on NN potentials

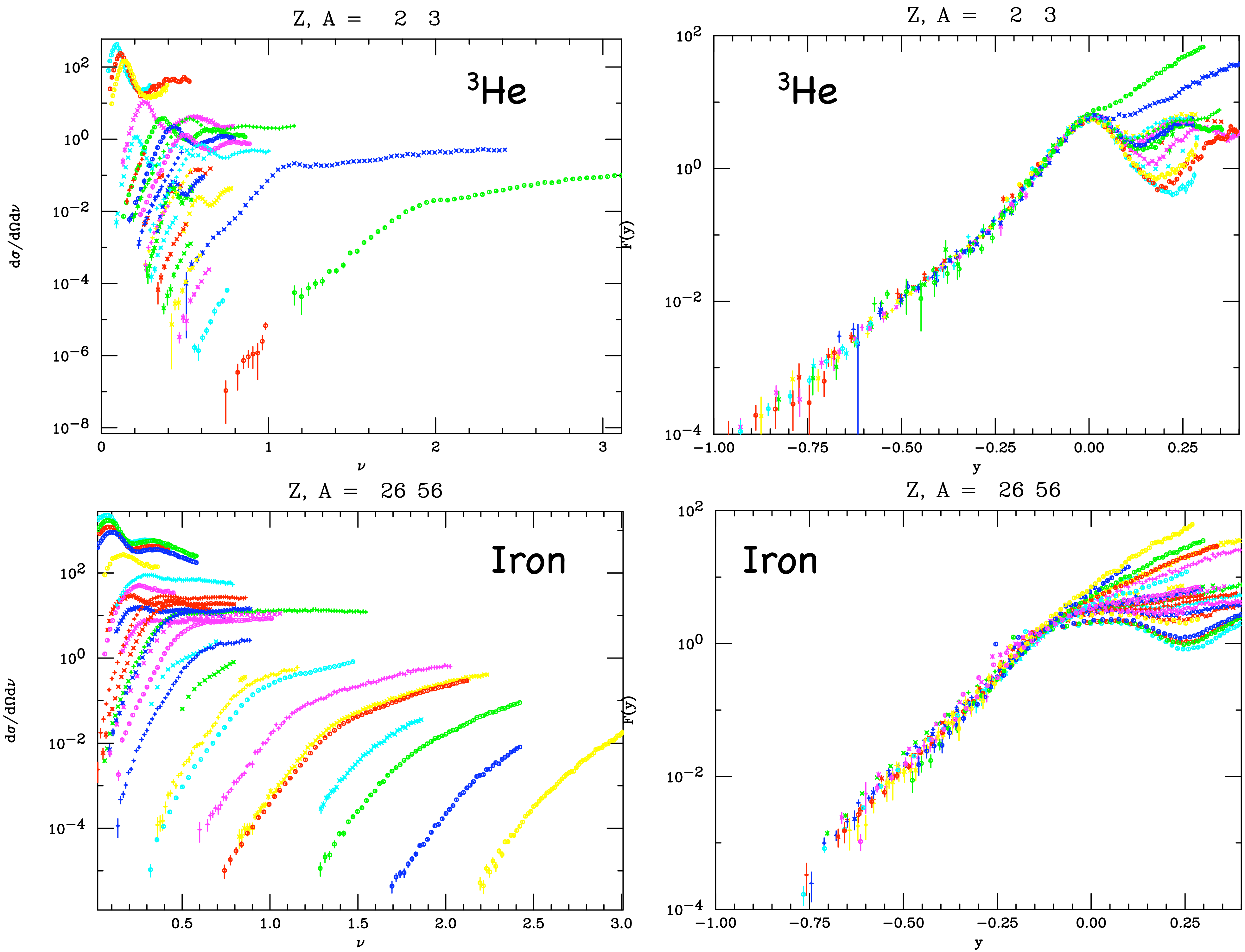
S(k,E=2.2MeV) = n(k)

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

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

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

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



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.

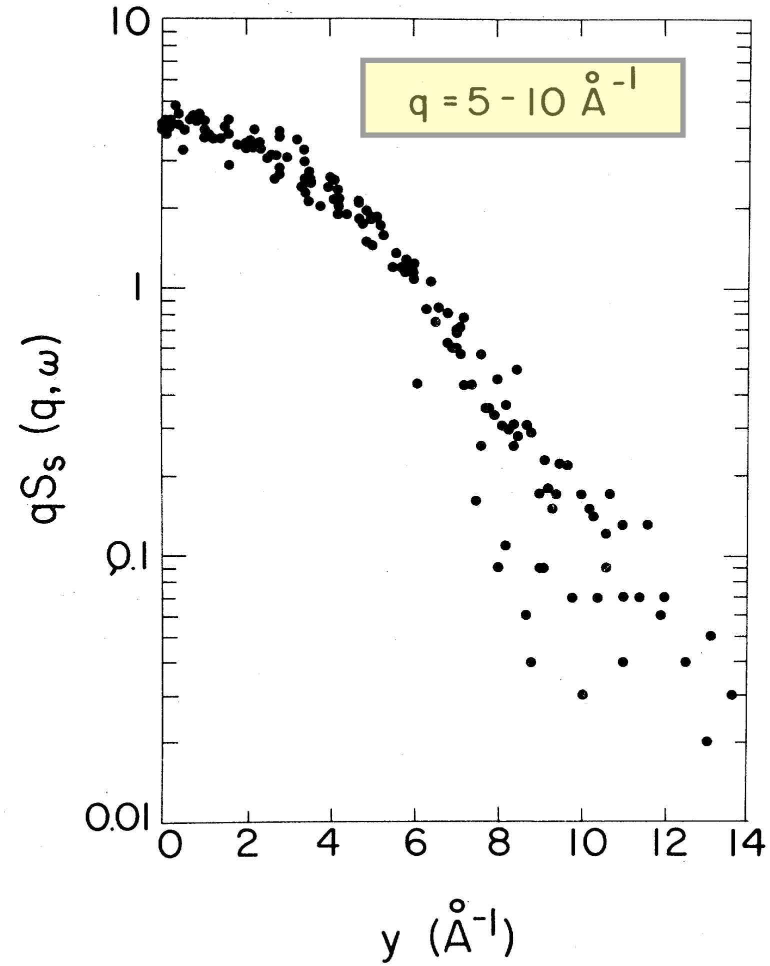


FIG. 1. y scaling in liquid neon. $qS_s(q,\omega)$ is shown in arbitrary units as a function of $y=(m/\hbar q)(\omega-\omega_r)$ for liquid neon at $T=26.9$ K for the eleven values of q in the range 5.0—10.0 Å^{-1}, which were used in the determination of the momentum distribution in Ref. 7. The data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

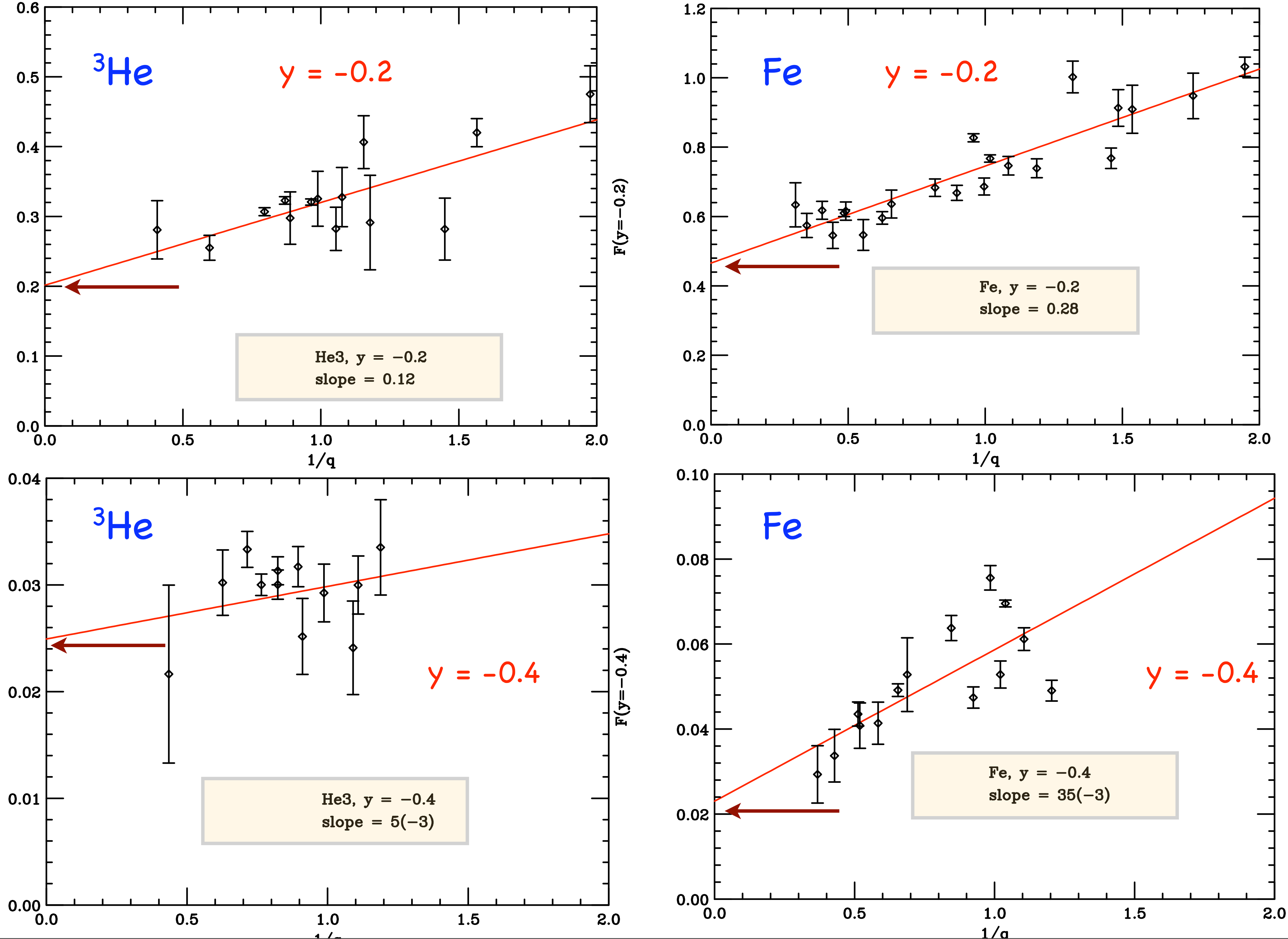
Momentum distributions are "distorted" by the presence of FSI

y-scaling as a test for presence of FSI

FSI have a 1/q dependence

Weinstein & Negele PRL 49 1016 (1982)

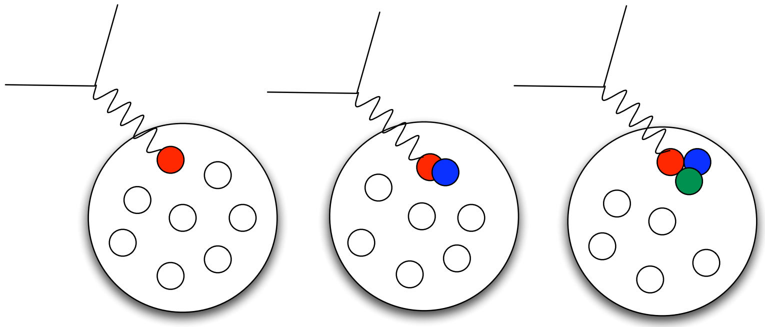
Convergence of F(y,q)



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.

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

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

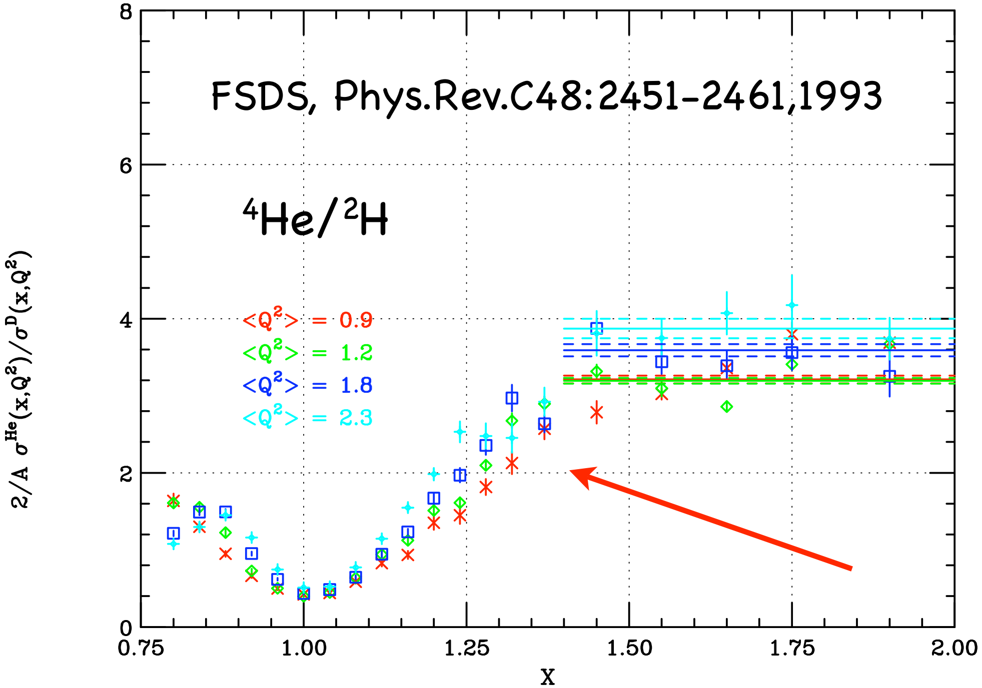
$$\frac{3}{A}\frac{\sigma_A(x,Q^2)}{\sigma_{A=3}(x,Q^2)} = a_3(A)\Big|_{2<x\leq 3}$$

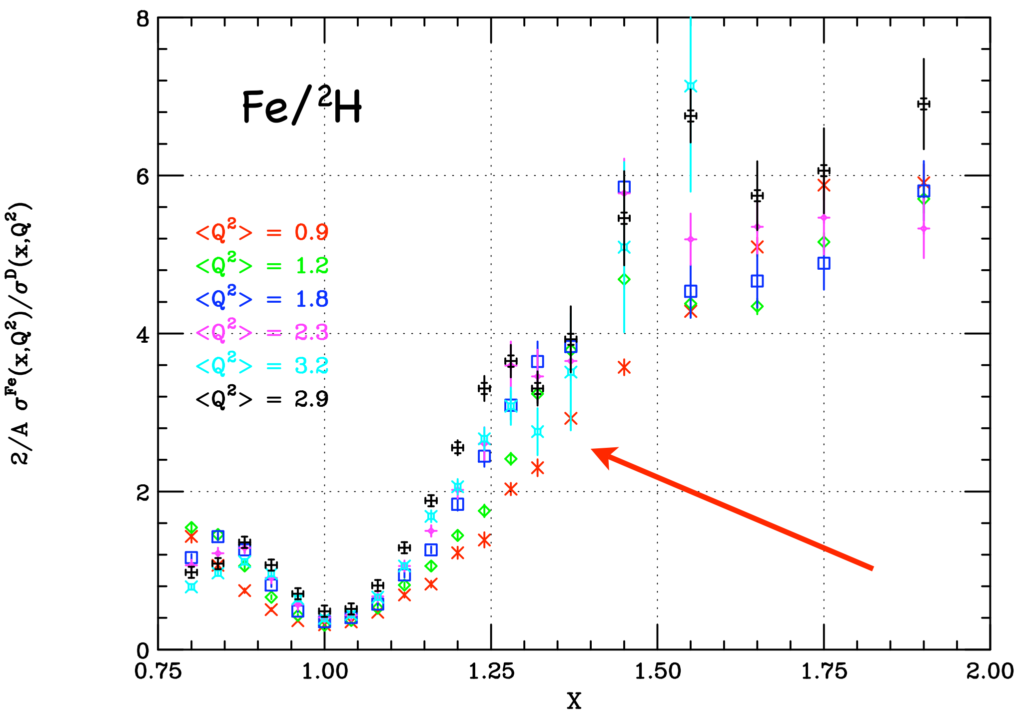
In the ratios, off-shell effects and FSI largely cancel.

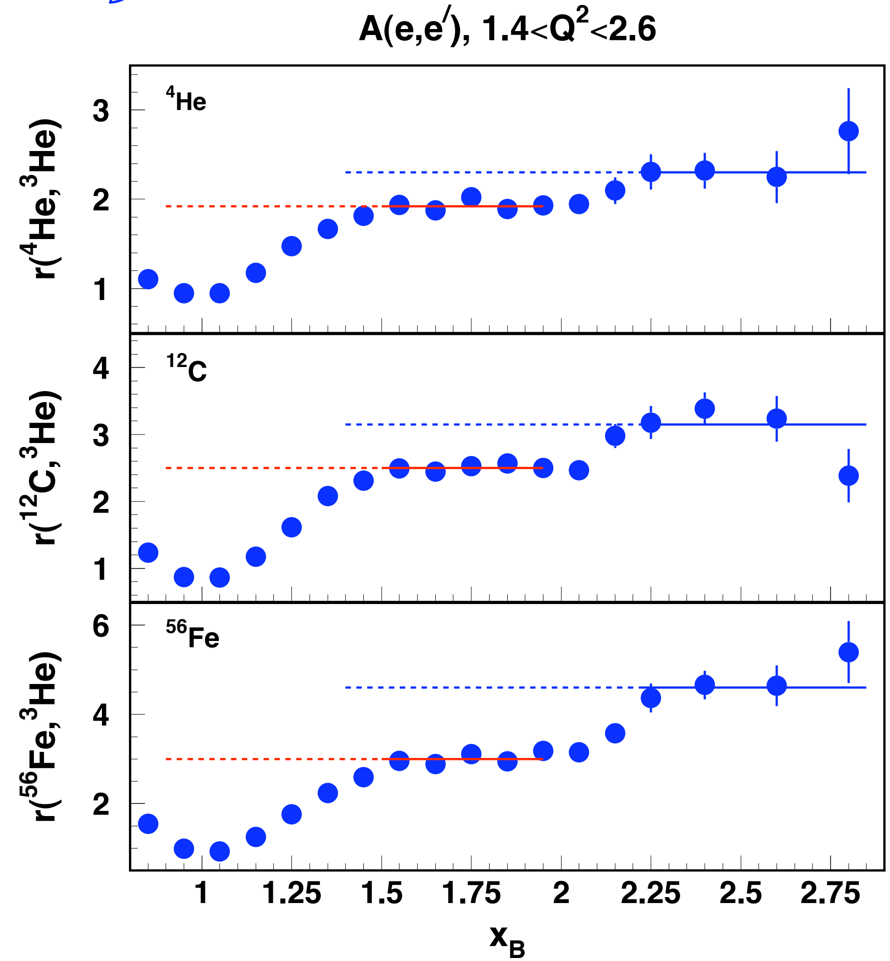
$a_j(A)$ is proportional to probability of finding a j-nucleon correlation

Ratios, SRC's and Q^2 scaling

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







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

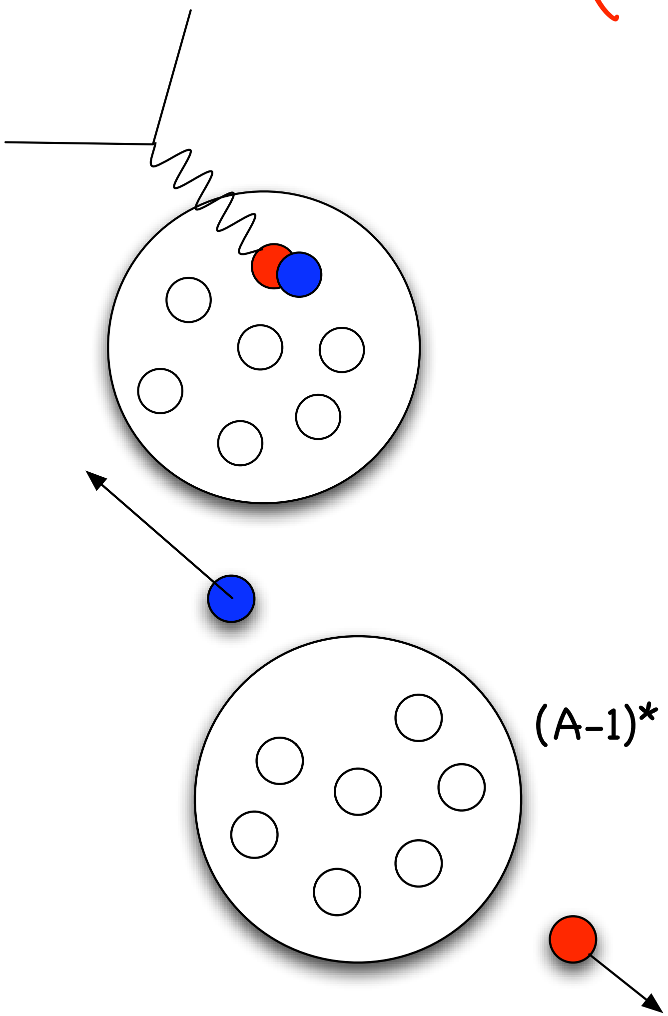
CLAS data
Egiyan et al., PRL 96, 082501, 2006

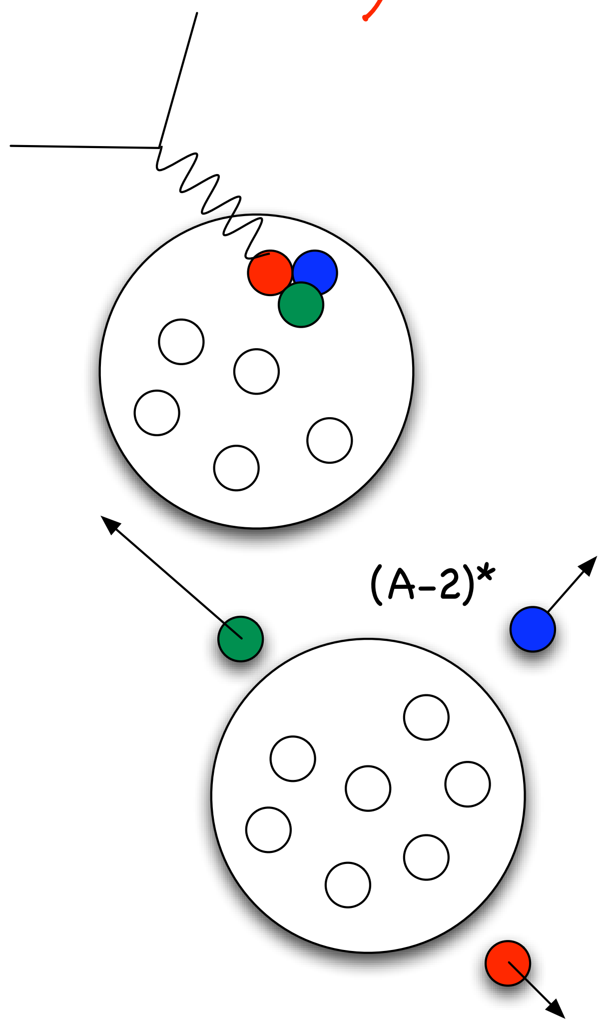
$a_j(A)$ is probability of finding a j-nucleon correlation

Knocking out a nucleon in a two-nucleon pair

α_{tn}: light cone variable for interacting nucleon belonging to correlated nucleon pair

$$\alpha_{tn} = 2 - \frac{q_- + 2m}{2m}\left(1 + \frac{\sqrt{W^2 - 4m^2}}{W}\right) \to x \qquad (Q^2 >>)$$





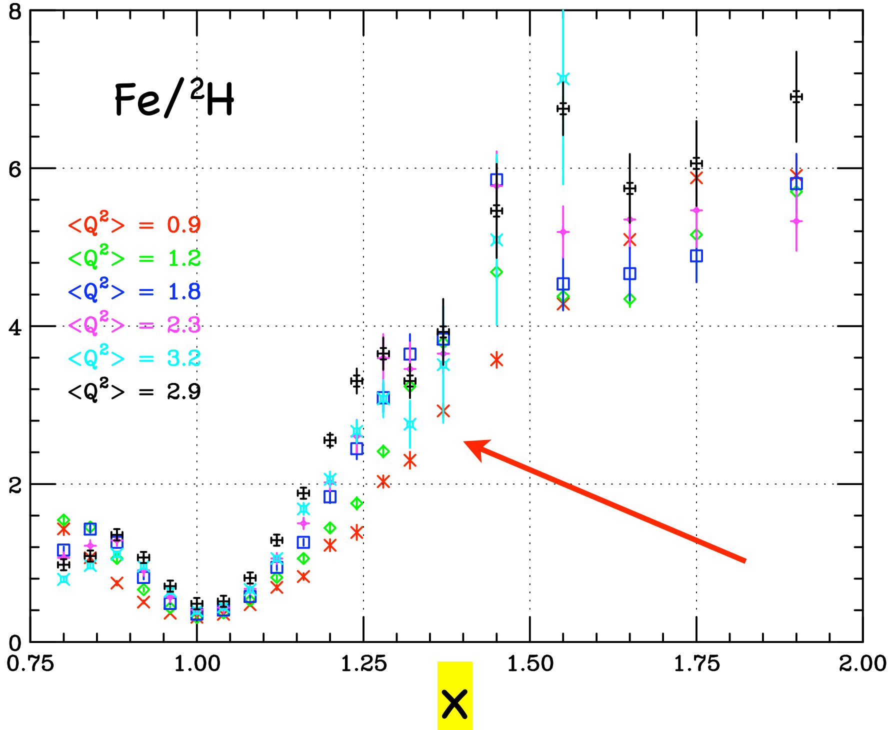
$F_2(\alpha_{tn})$

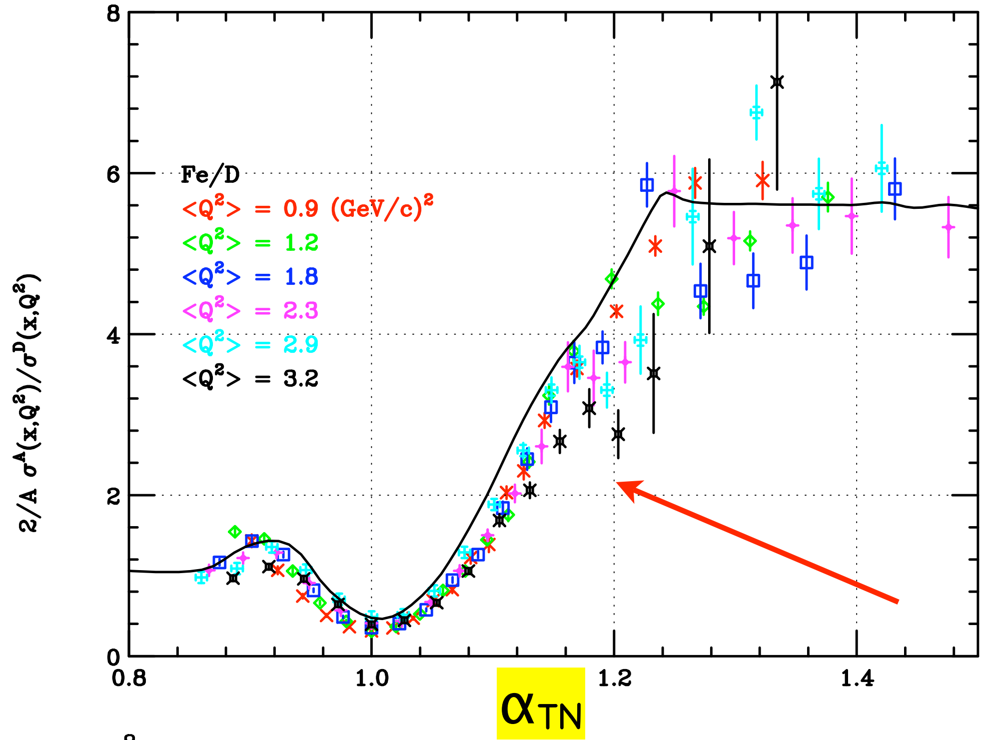
Ratios

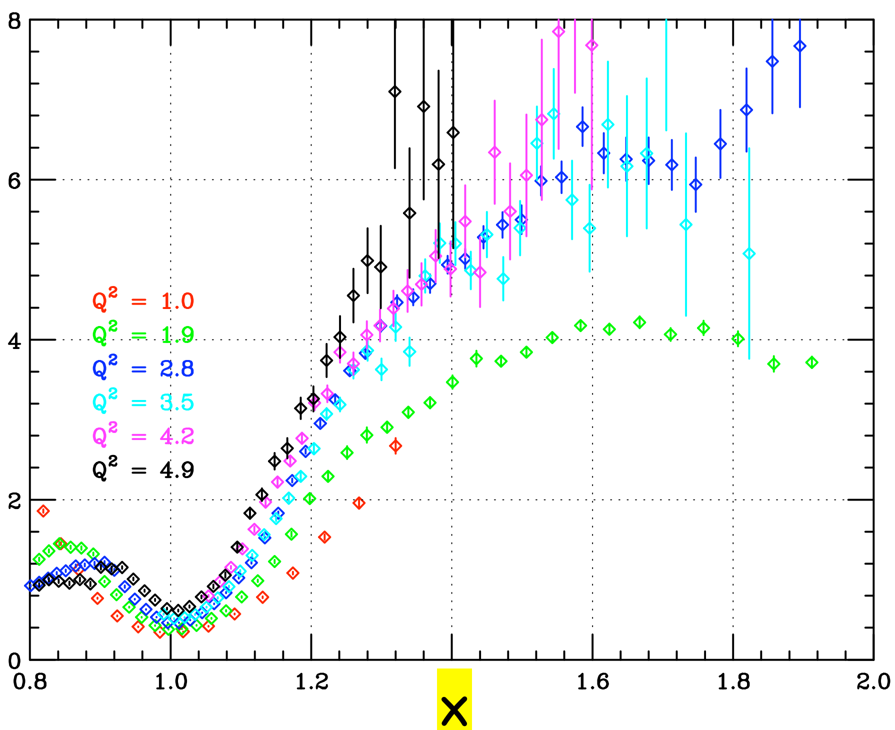
Accounts for Q^2 dependence

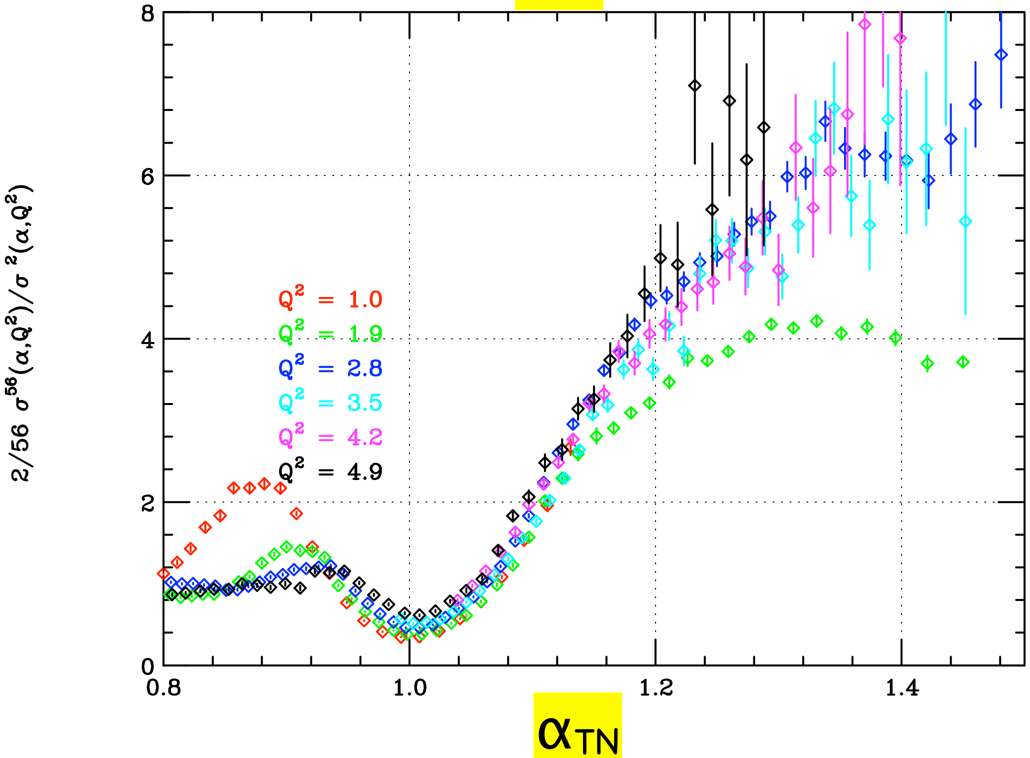
FSDS, Phys.Rev.C48:2451-2461,1993

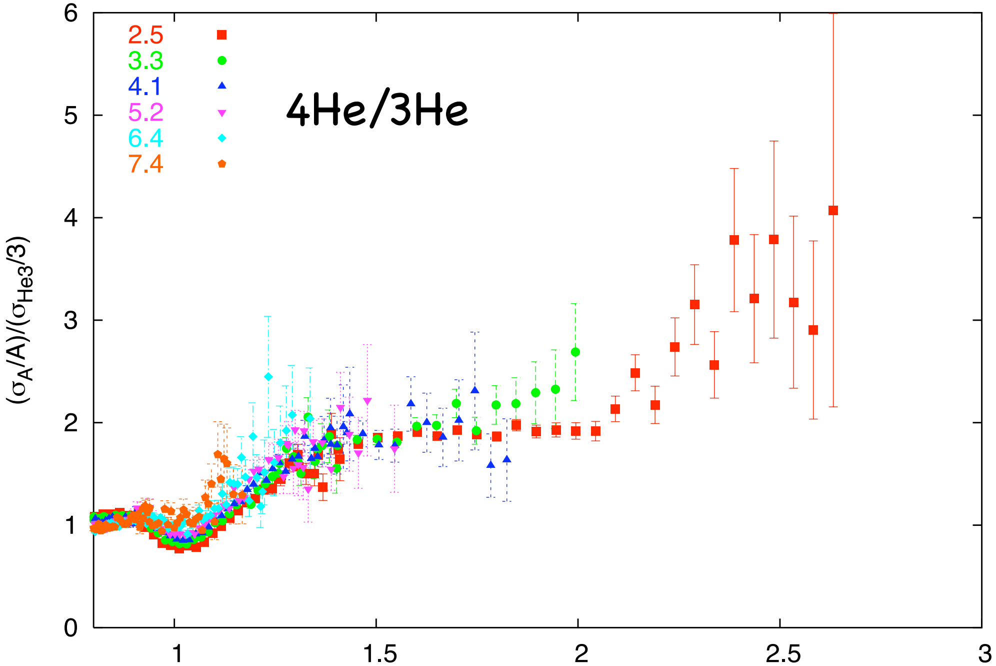
Ratios of Fe/2H

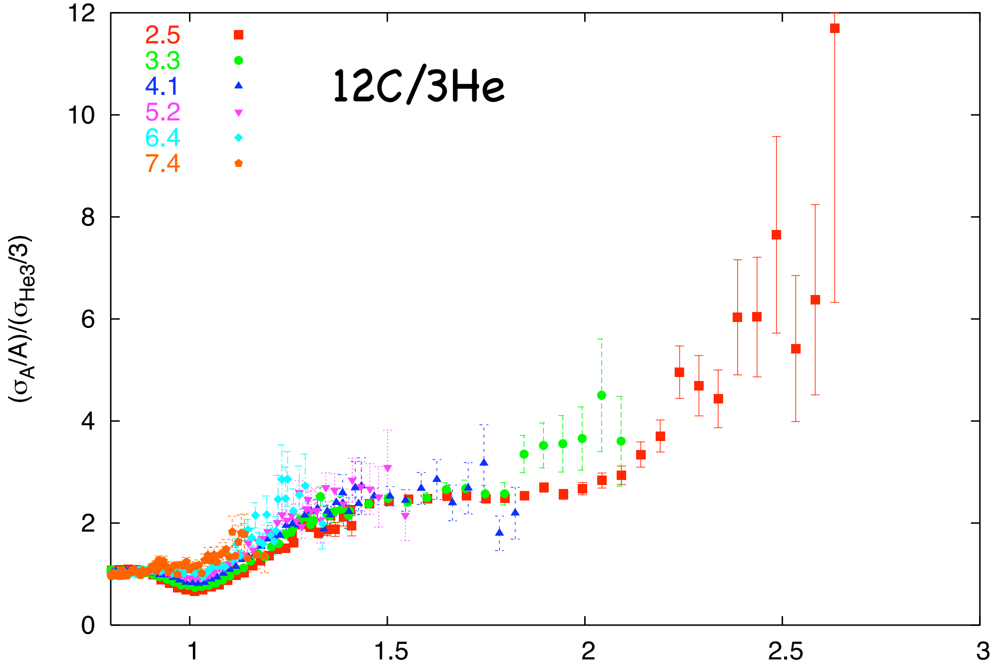




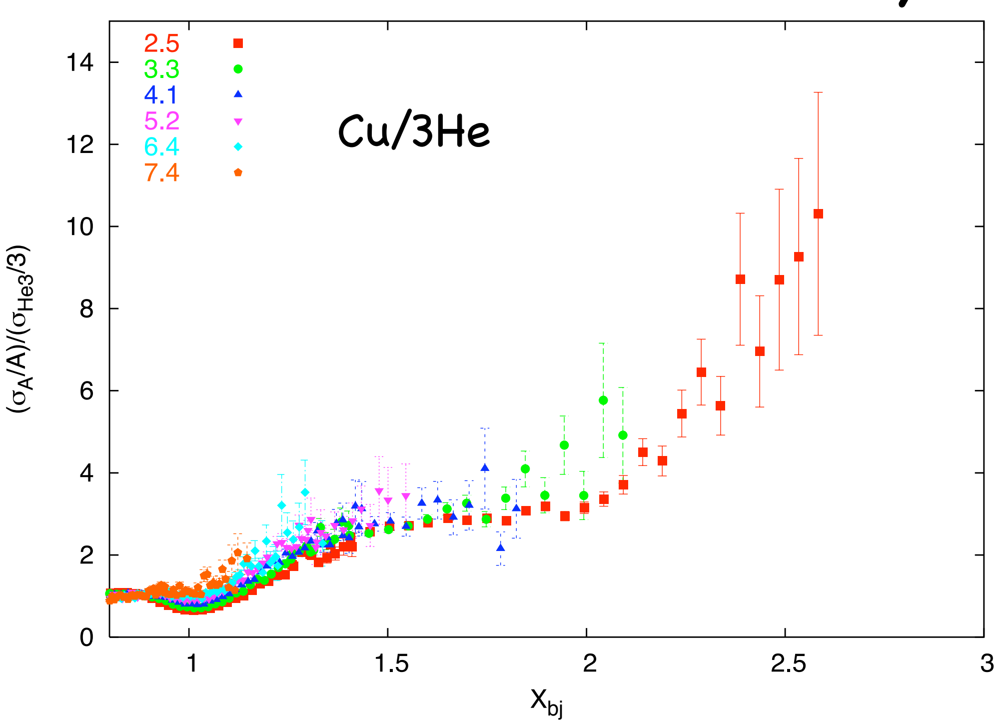


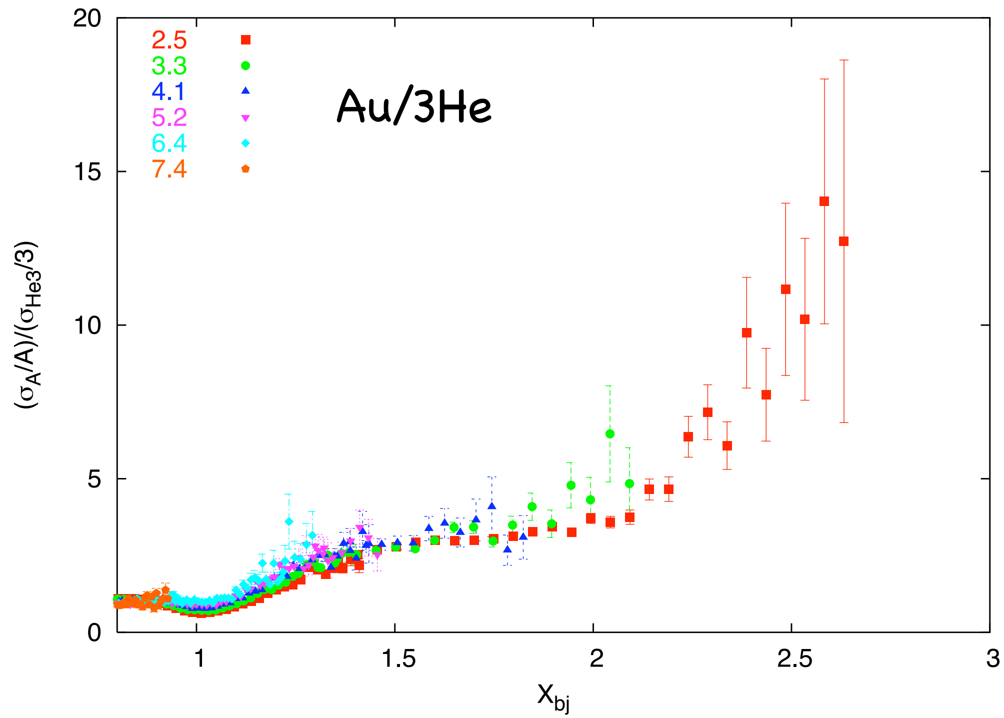






Preliminary Results (E02-019)

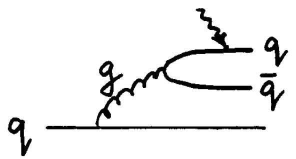


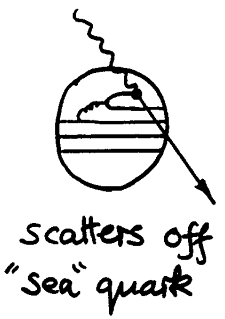


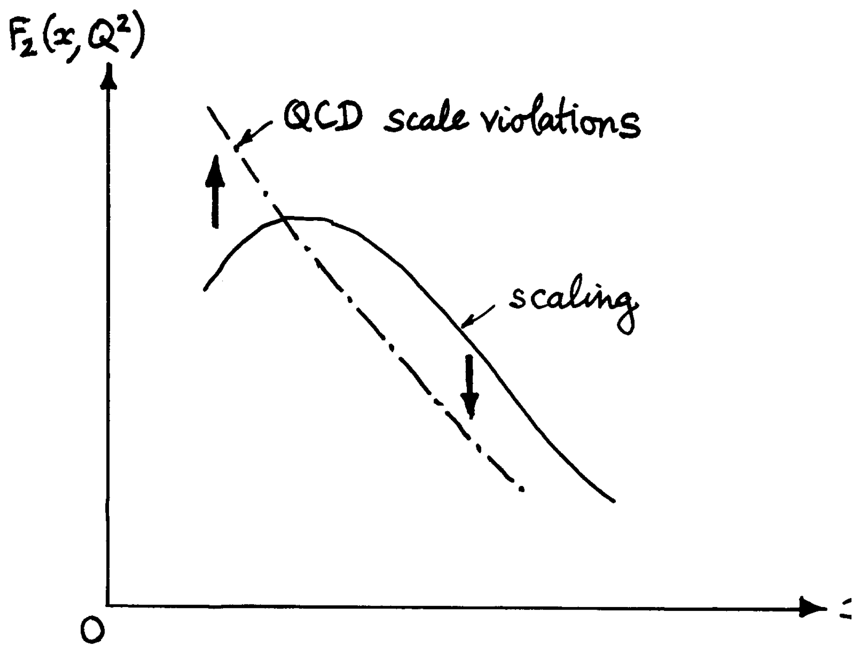
Scaling in DIS

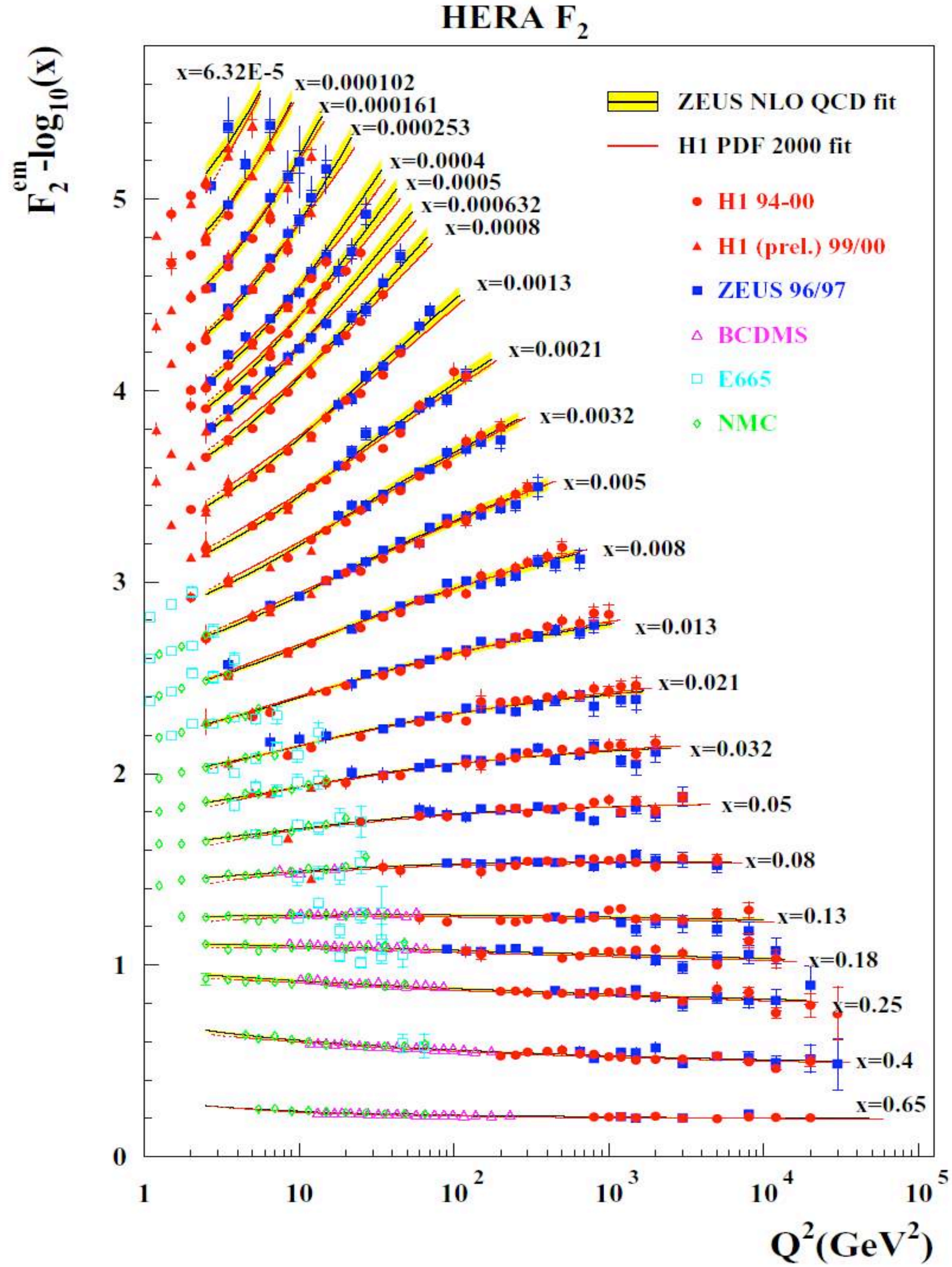
$$F_2(x, Q^2) \rightarrow F_2(x)$$

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









Bloom-Gilman duality

BG observed that, at low hadronic final state mass, W, (strongly Q^2 dependent) the inclusive structure function effectively follows a global scaling curve which delineates high-W data (Q^2 independent).

The resonance structure function averages to this global scaling curve

$$\frac{2M}{Q^2}\int_0^{\nu_m} d\nu\, \nu W_2(\nu, Q^2) = \int_1^{\omega'_m} d\omega'\, \nu W_2(\omega')$$

Measured structure functions (dependent on ν Q^2)

Scaling function (dependent on ω′ only)

Hadrons

Quarks

$$\omega' = \frac{1}{x} + \frac{M^2}{Q^2}$$

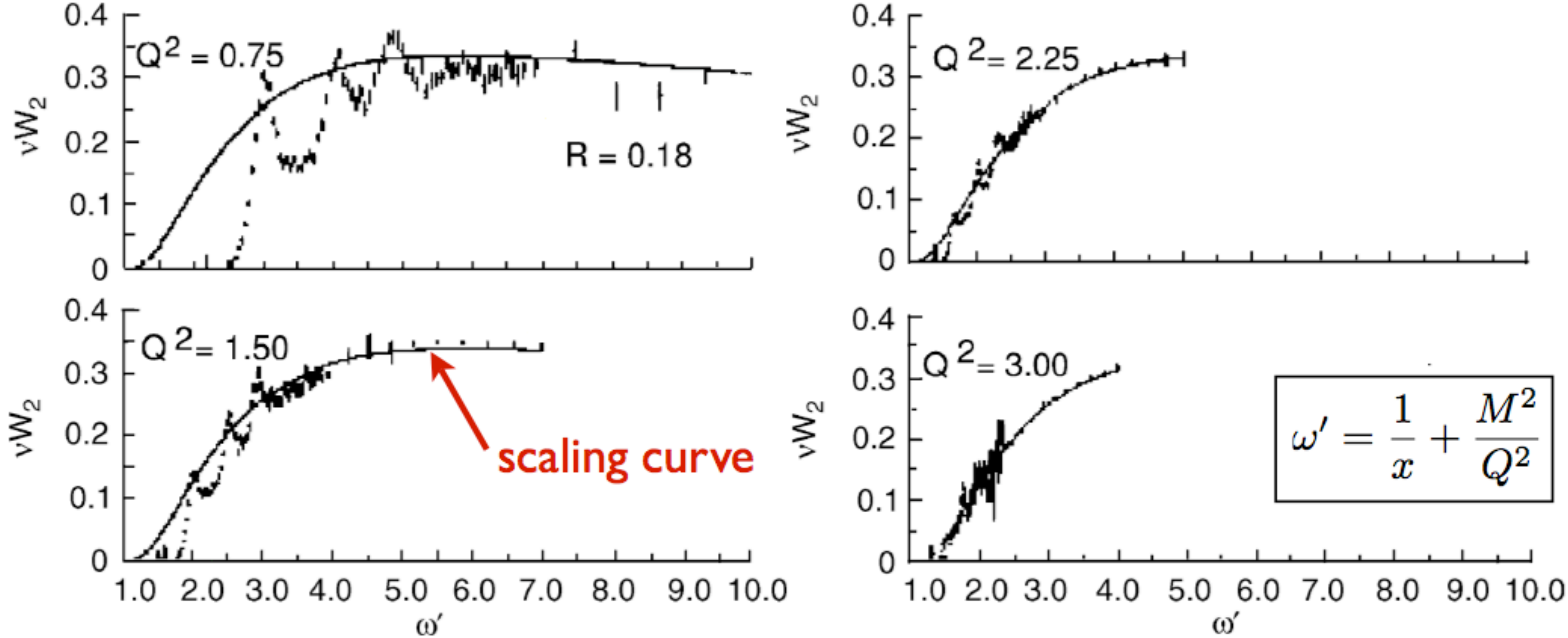
FESR

Empirically discovered scaling variable

Bloom and Gilman PRD 4 (2901) 1971

Bloom-Gilman duality

resonance - scaling duality in proton structure function $\nu W_2 = F_2$



$$\omega' = \frac{1}{x} + \frac{M^2}{Q^2}$$

$$\frac{2M}{Q^2}\int_0^{\nu_m} d\nu\, \nu W_2(\nu, Q^2) = \int_1^{\omega'_m} d\omega' \nu W_2(\omega')$$

Bloom and Gilman PRD 4 (2901) 1971

Duality in QCD

A. De Rújula, H. Georgi, H.D. Politzer reformulated BG duality in terms of an operator product (or "twist") expansion of moments of structure functions.

expand moments of structure functions in powers of $1/Q^2$

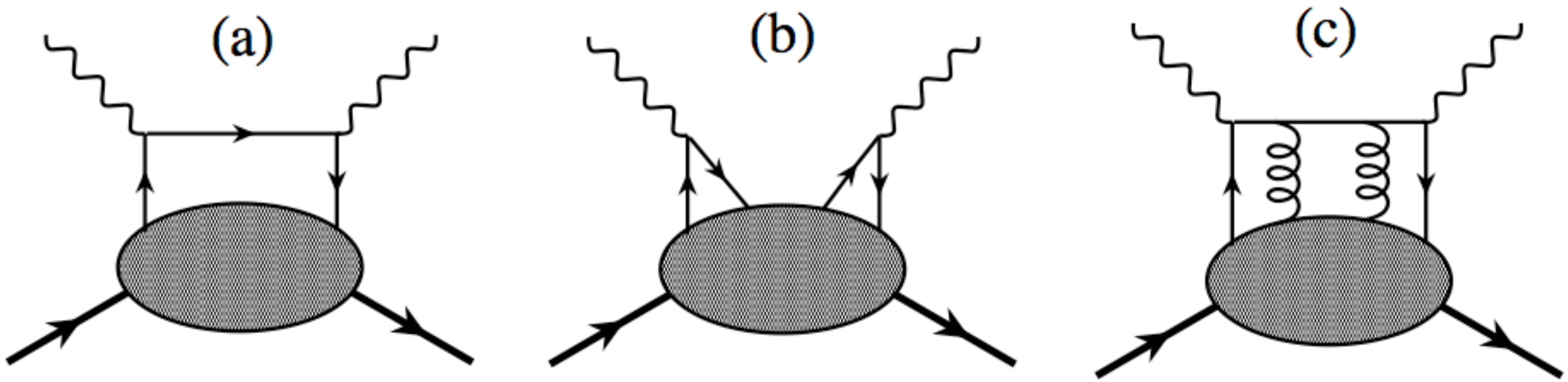
$$
\begin{aligned}
M_n(Q^2) &= \int_0^1 dx\, x^{n-2} F_2(x, Q^2) \\
&= \sum_{i=2,4,\cdots} \frac{A_i^{(n)}}{Q^{i-2}} \\
&= A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots
\end{aligned}
$$

matrix elements of operators with specific "twist" τ

τ = dimension - spin

The leading twist (twist-2) term, $A^{(n)}$, corresponds to scattering from free partons, and is responsible for the scaling of the structure functions. The higher twist terms $A^{(n)}{}_{i>2}$ involve multi-quark and mixed quark-gluon operators, and contain information on long-range, non-perturbative correlations between partons.

Duality in QCD



$\tau = 2$

single quark scattering

$\bar{\Psi}\gamma_\mu\Psi$

$\tau > 2$

qq and qg correlations

$\bar{\Psi}\gamma_\mu\Psi\bar{\Psi}\gamma_\nu\Psi$

$\bar{\Psi}\widetilde{G}_{\mu\nu}\gamma^\nu\Psi$

If moment ≈ independent of Q^2 then higher twist terms are small

Existence of Duality suggests that higher twists are suppressed and data at low Q^2 at high x might allow extraction of the PDFs where they are very poorly known.

Left unanswered: why specific multi-parton correlations were suppressed, and how the physics of resonances gave way to scaling.

ξ scaling

The Nachtmann variable (fraction ξ of the nucleon light cone momentum p^+) has been shown (Georgi & Politzer) to be the variable in which logarithmic violations of scaling in DIS should be studied at finite Q^2

$$\xi \equiv -\frac{q^+}{p^+} = \frac{|\vec{q}| - \nu}{M} = \frac{2x}{1+\sqrt{1+4M^2x^2/Q^2}} \rightarrow x$$

If one wants to extract parton distribution functions (PDFs) from inelastic structure functions one must account for:

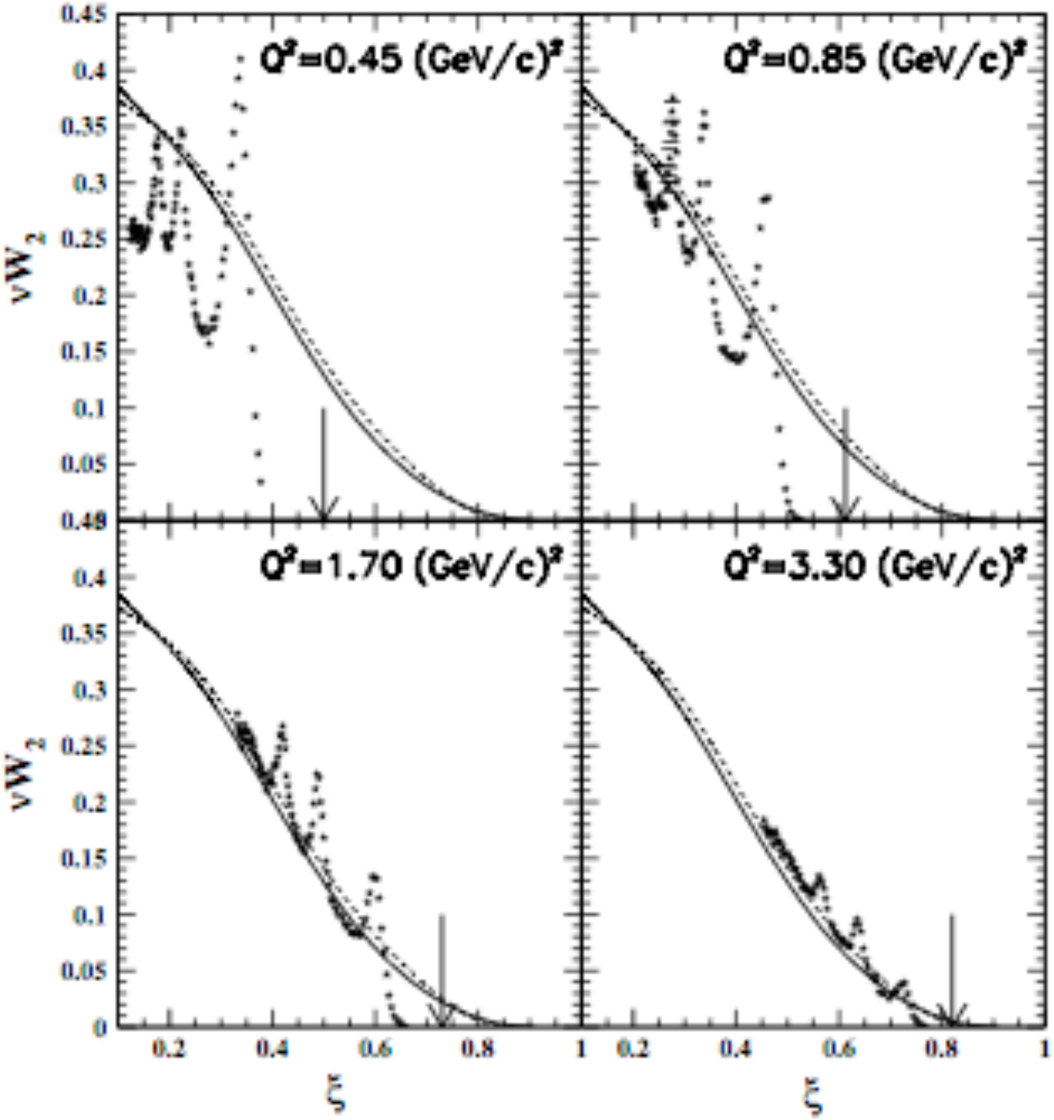
- dynamical power corrections (higher twists): go as Λ^2_{QCD}/Q^2
- target mass corrections: go as $x^2 M_n^2/Q^2$

ξ accounts for 'target mass effects'

Expanding ξ in powers of $1/Q^2$ at high Q^2 gives which is very similar to BG variable

$$\frac{1}{\xi} = \frac{1}{x} + \frac{xM^2}{Q^2}$$

Bloom-Gilman duality revisited at JLAB



Average over low hadronic final state mass, W, (strongly Q^2 dependent) ≈ high-W data (Q^2 independent) scaling curve

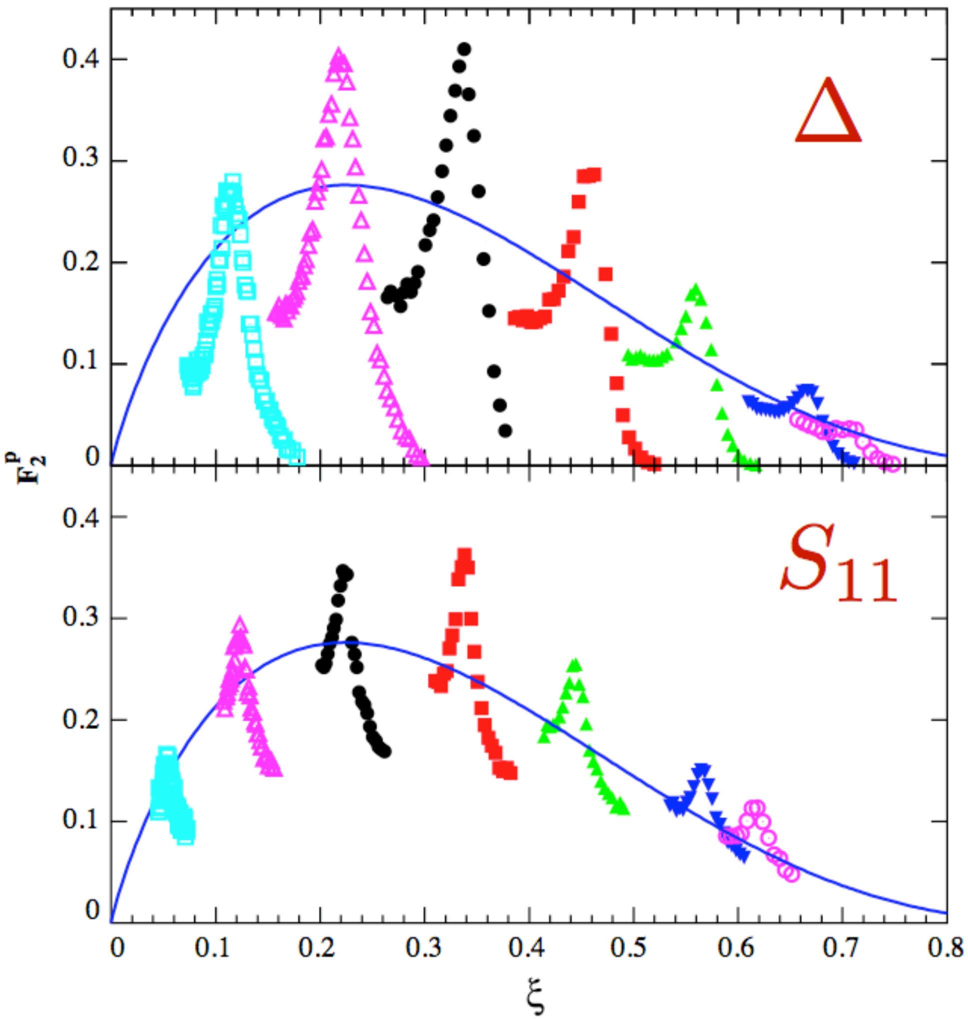
$$\xi = \frac{2x}{1 + \sqrt{1 + 4M^2x^2/Q^2}} \longrightarrow x$$

Nachtmann scaling variable

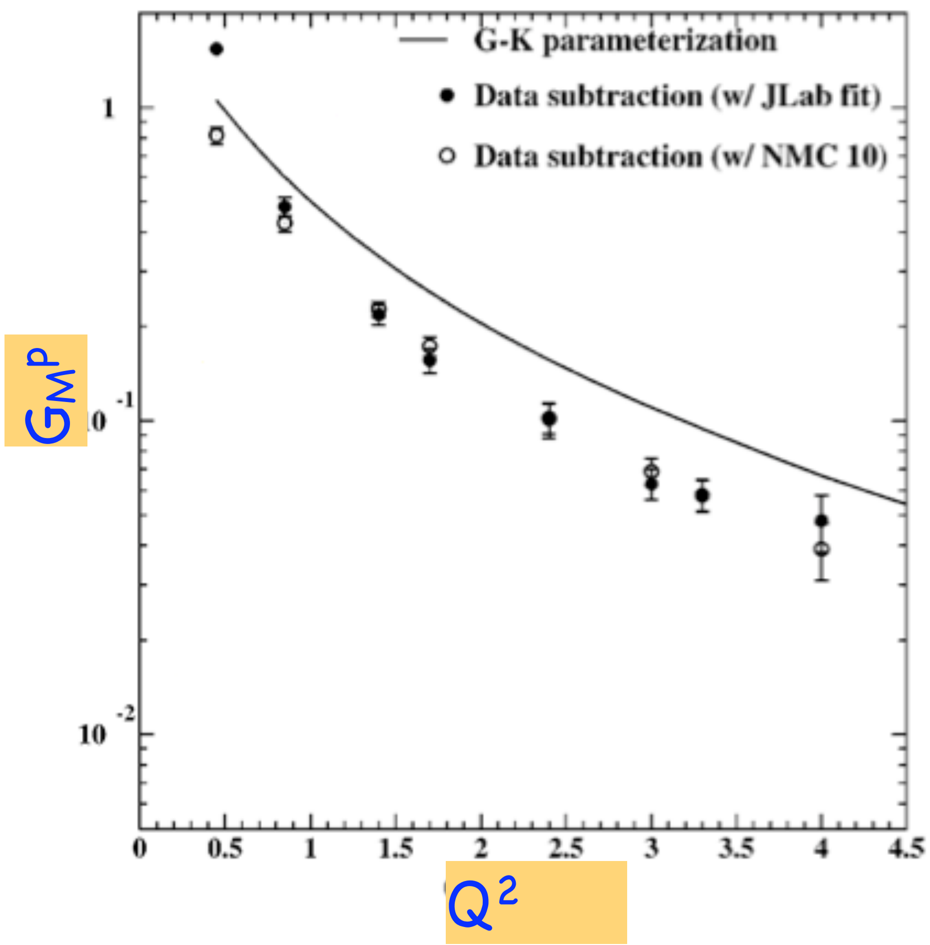
Niculescu et al., Phys. Rev. Lett. 85 (2000) 1182 and 1186

JLAB Hall C

Duality exists also in local regions, around individual resonances



And duality should be applicable to the elastic peak

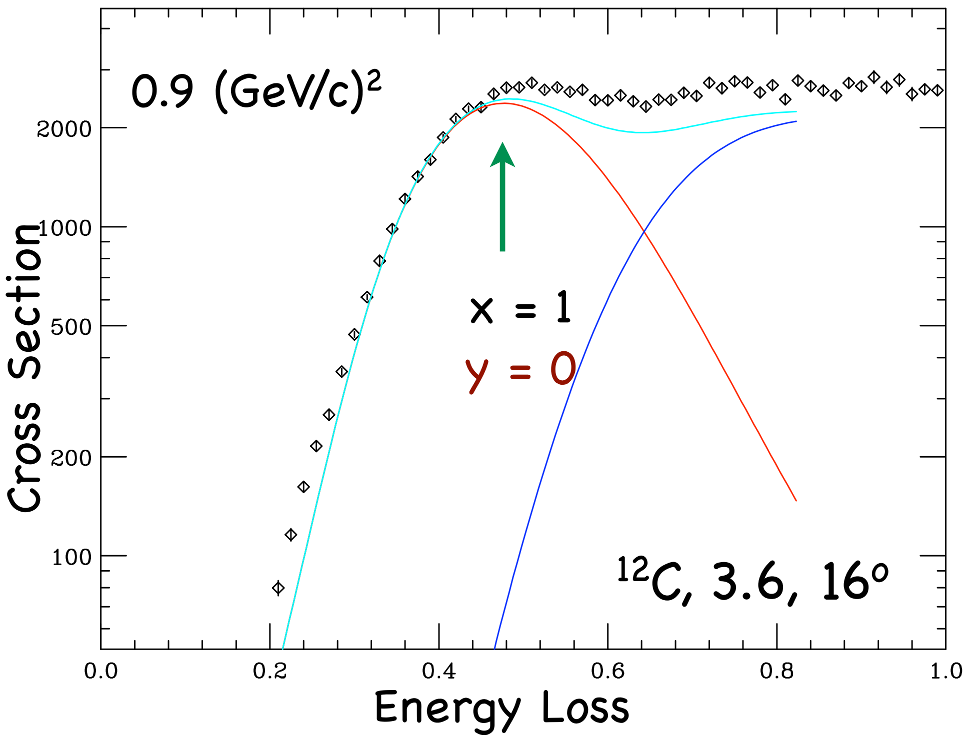


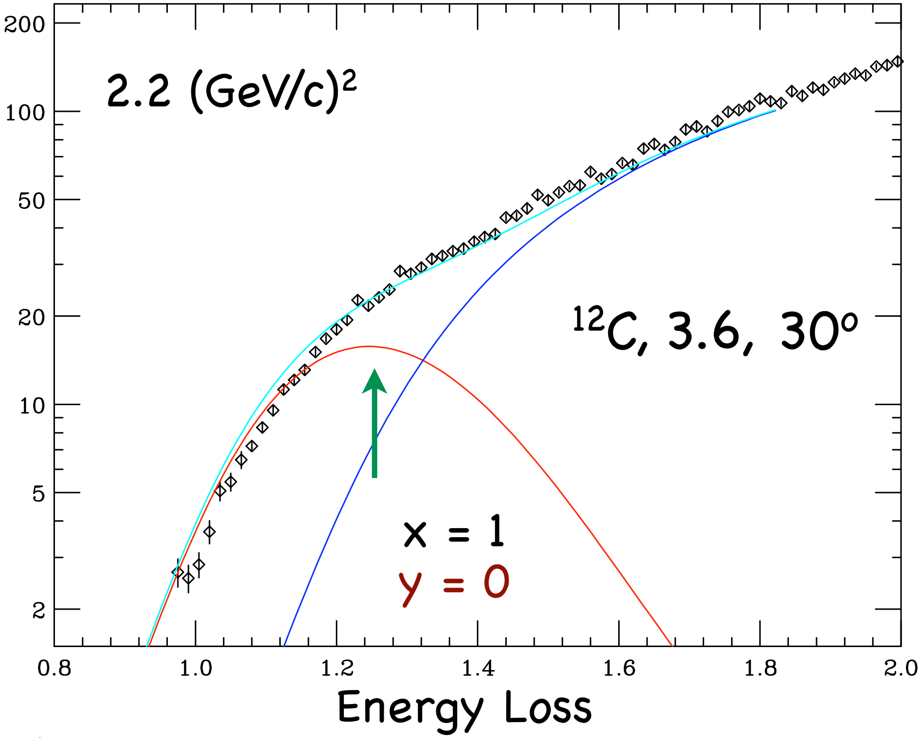
Ent et al PRD 63 038302

x and ξ scaling in the x > 1 region

- Increasing inelastic contribution
- As Q^2 increases we see for evidence scaling in x and ξ.
  - How is it that the quasielastic and inelastic pieces conspire to produce this scaling?
    - Is it accidental?
    - Is this a form of duality?
  - Do the dense configurations in the nucleus allow the partons to escape their parent and gain momentum from other nucleons?
    - Are there superfast quarks in the nucleus?

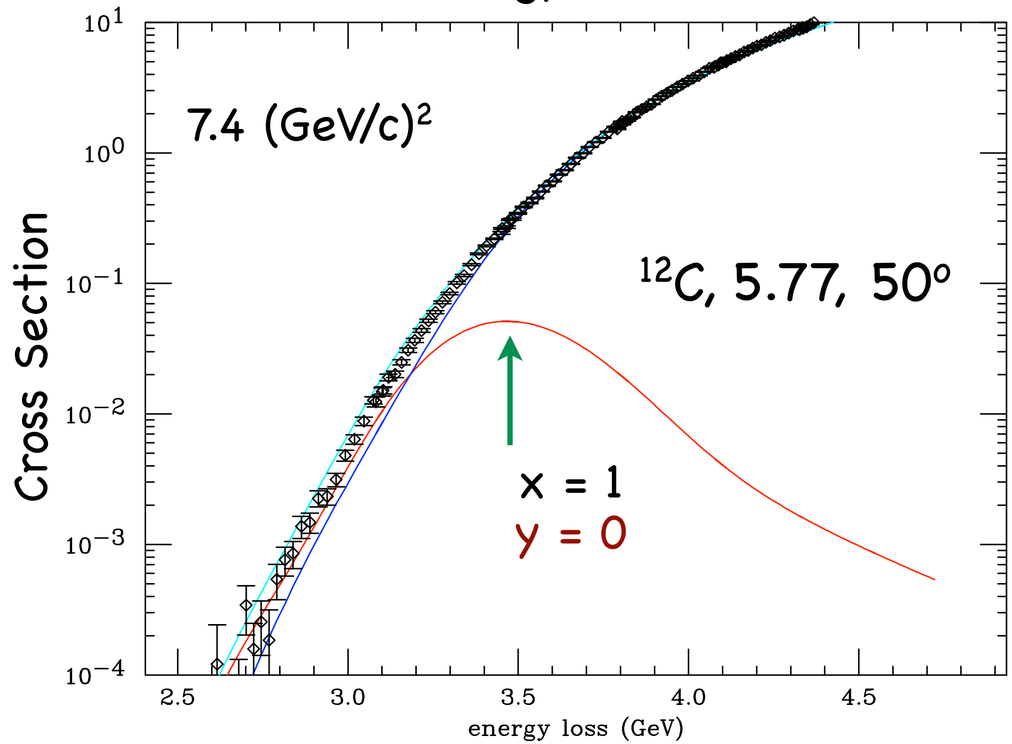
Inelastic contribution increases with Q^2



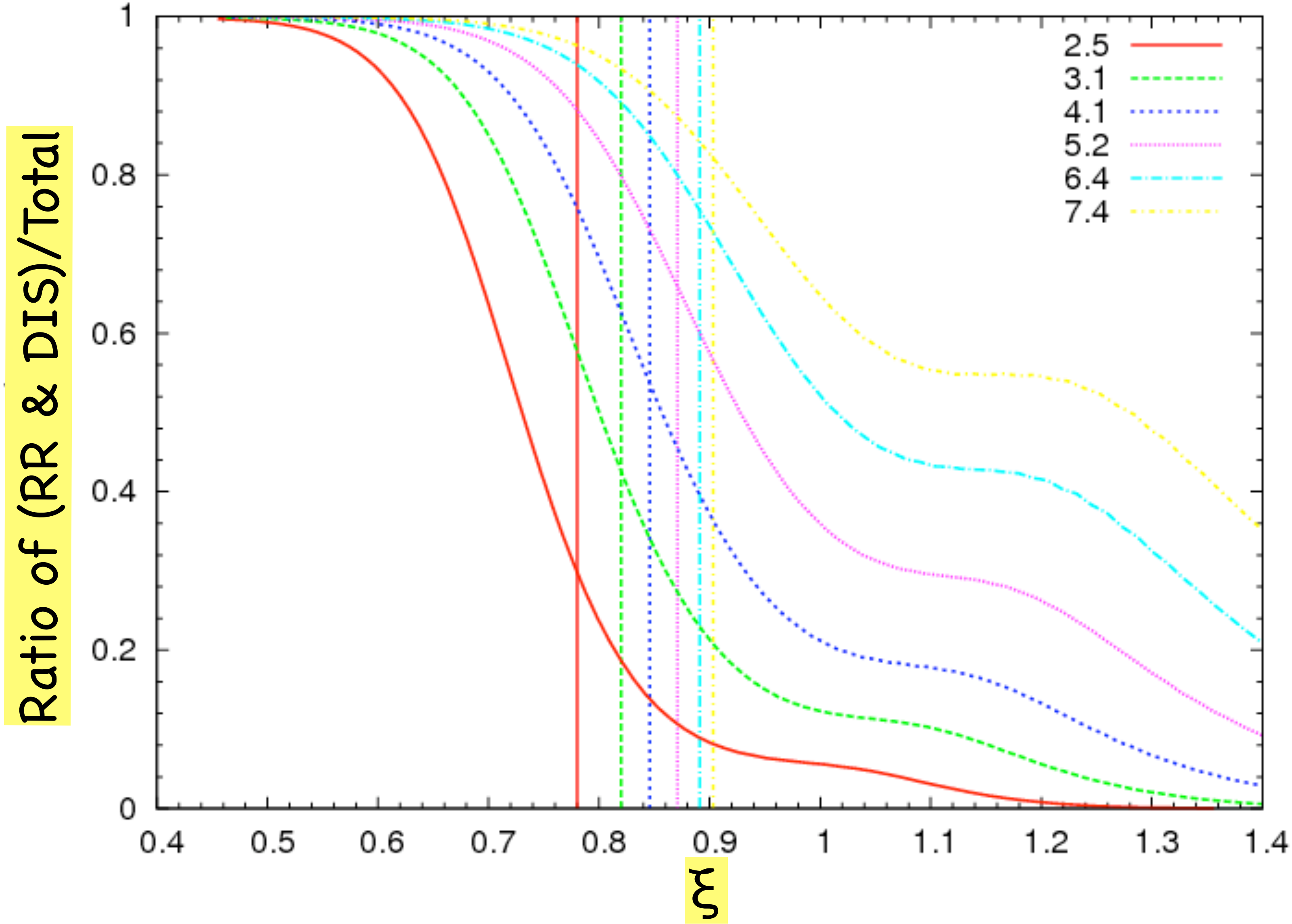


DIS begins to contribute at x > 1, y < 0 Convolution model

We expect that as Q^2 increases to see evidence (x-scaling) that we are scattering from a quark. How has it obtained its momenta?



Inelastic contribution at x = 1

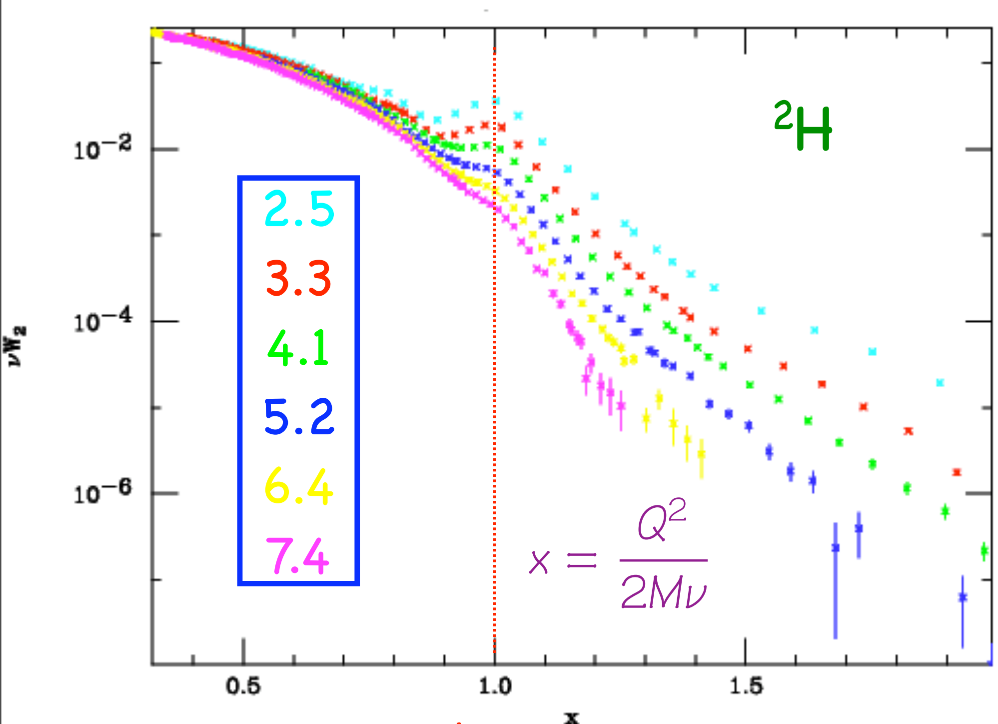


2.5 => 0.784
3.1 => 0.82
4.1 => 0.846
5.2 => 0.871
6.4 => 0.891
7.4 => 0.903

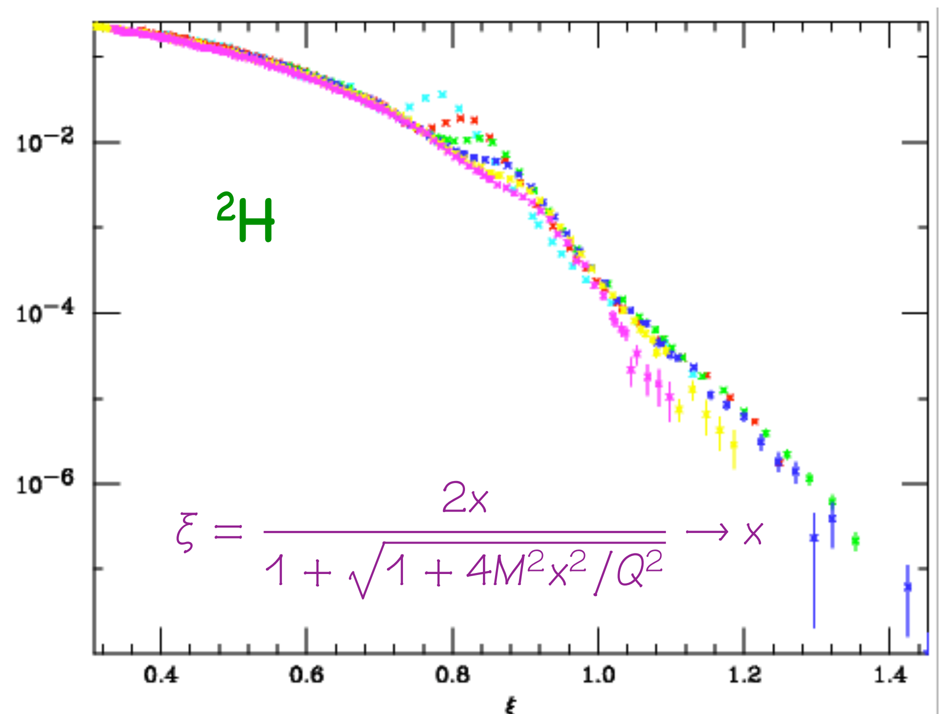
Ranges from 30% at Q^2 = 2.5 to 80% at Q^2 = 7.4

x and ξ scaling

An alternative to y-scaling is to present the data is presented in terms of scattering from individual quarks



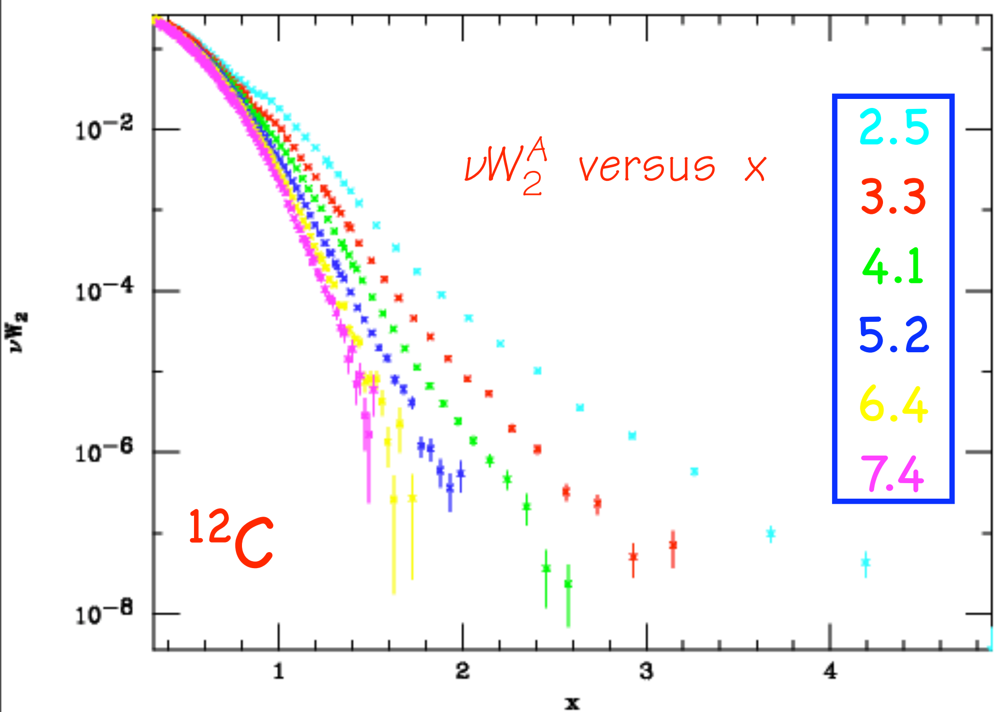
νW_2^A versus x

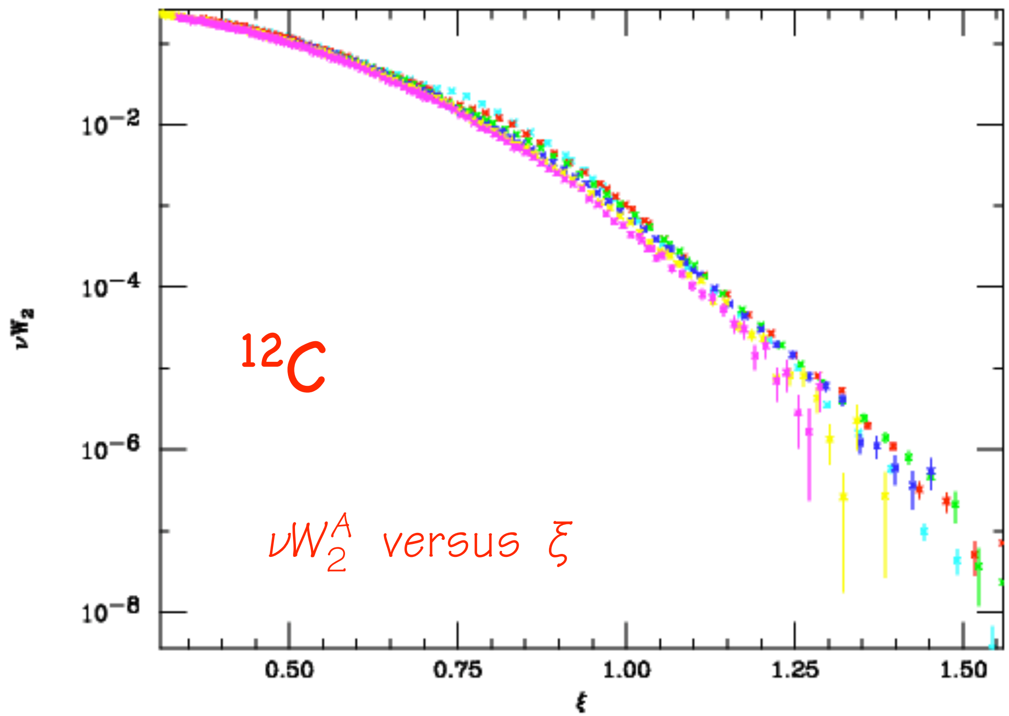


νW_2^A versus ξ

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

x and ξ scaling



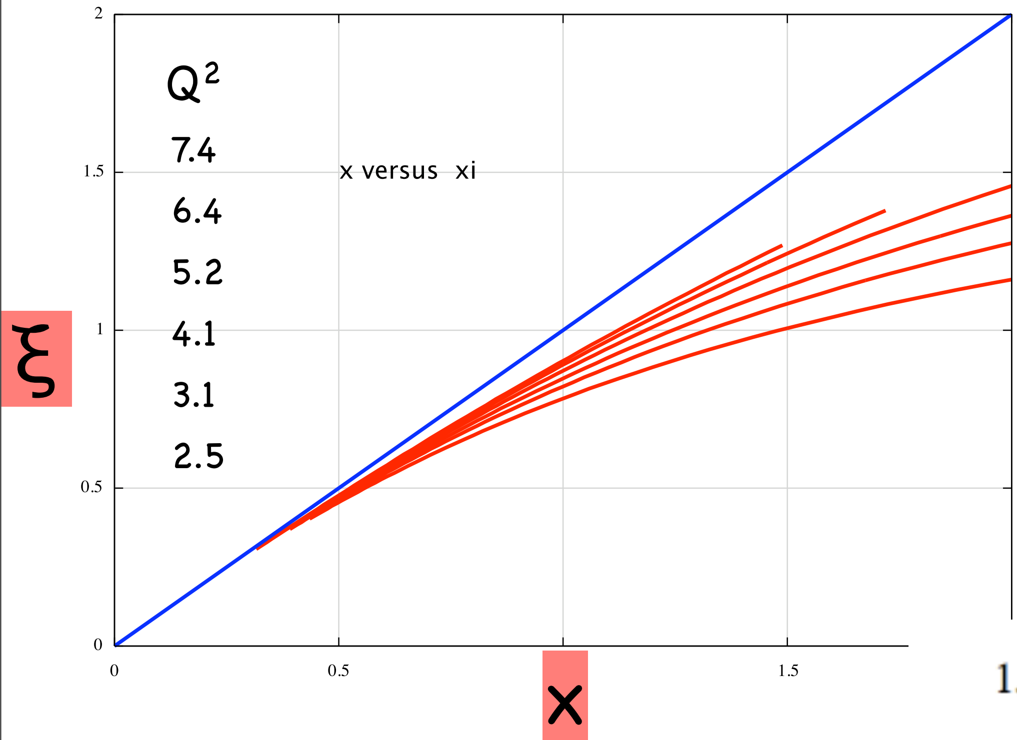


$$\underbrace{F_2^A(\xi) = \int_\xi^A dz F(z) F_2^n(\xi/z)}_{\text{averaging}}$$

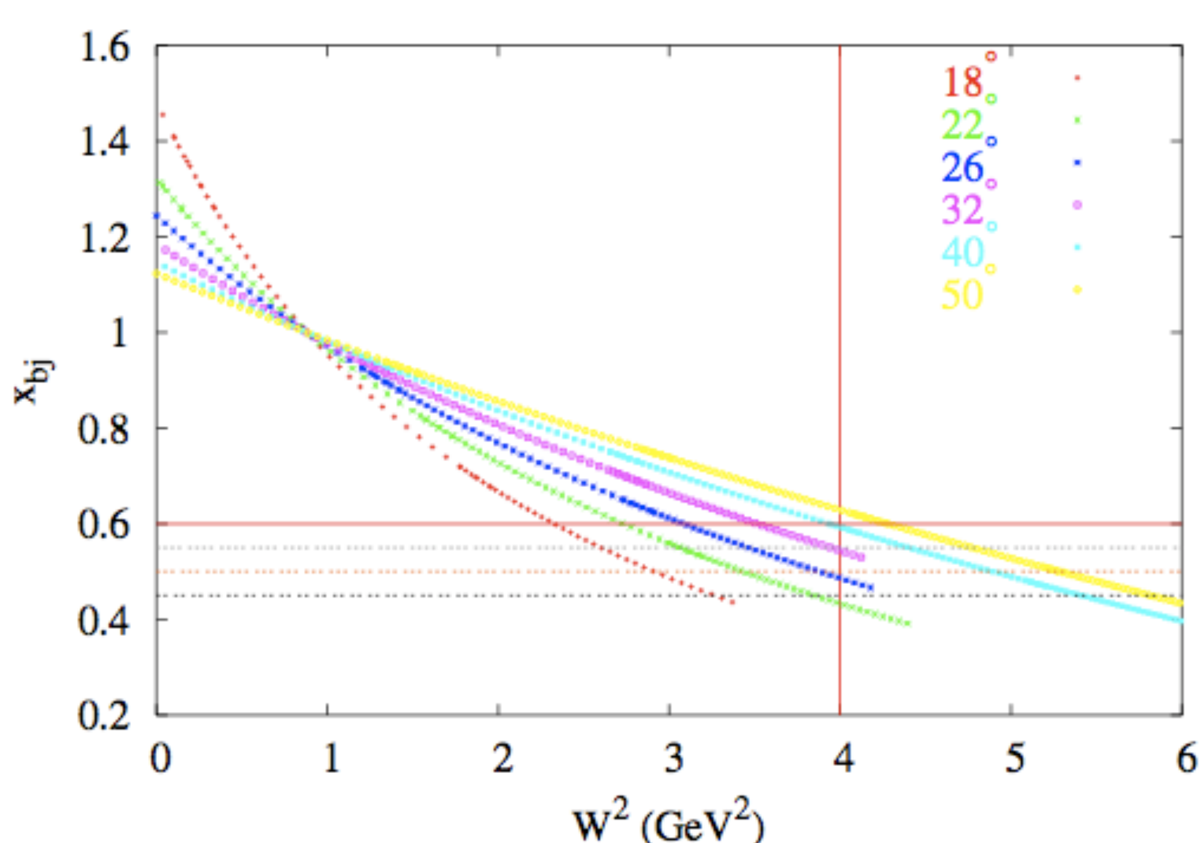
Local duality (averaging over finite range in x) should also be valid for elastic peak at x = 1 if analyzed in ξ

Evidently the inelastic and quasielastic contributions collude to produce ξ scaling. Is this a form of duality?

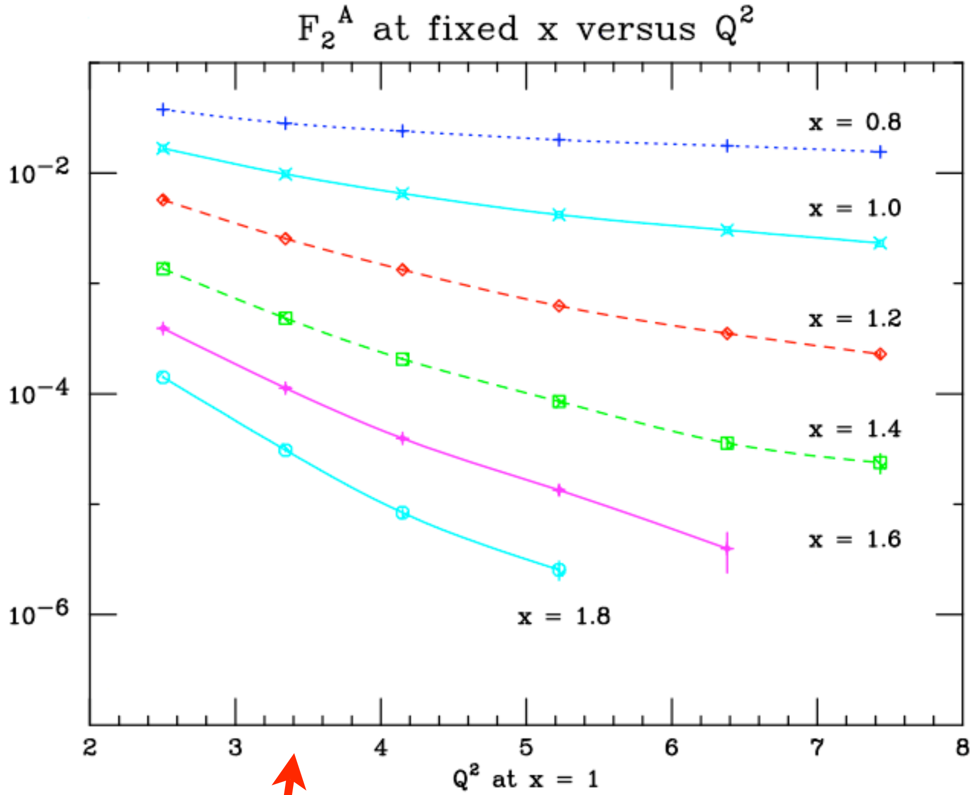
ξ and x



x versus W²

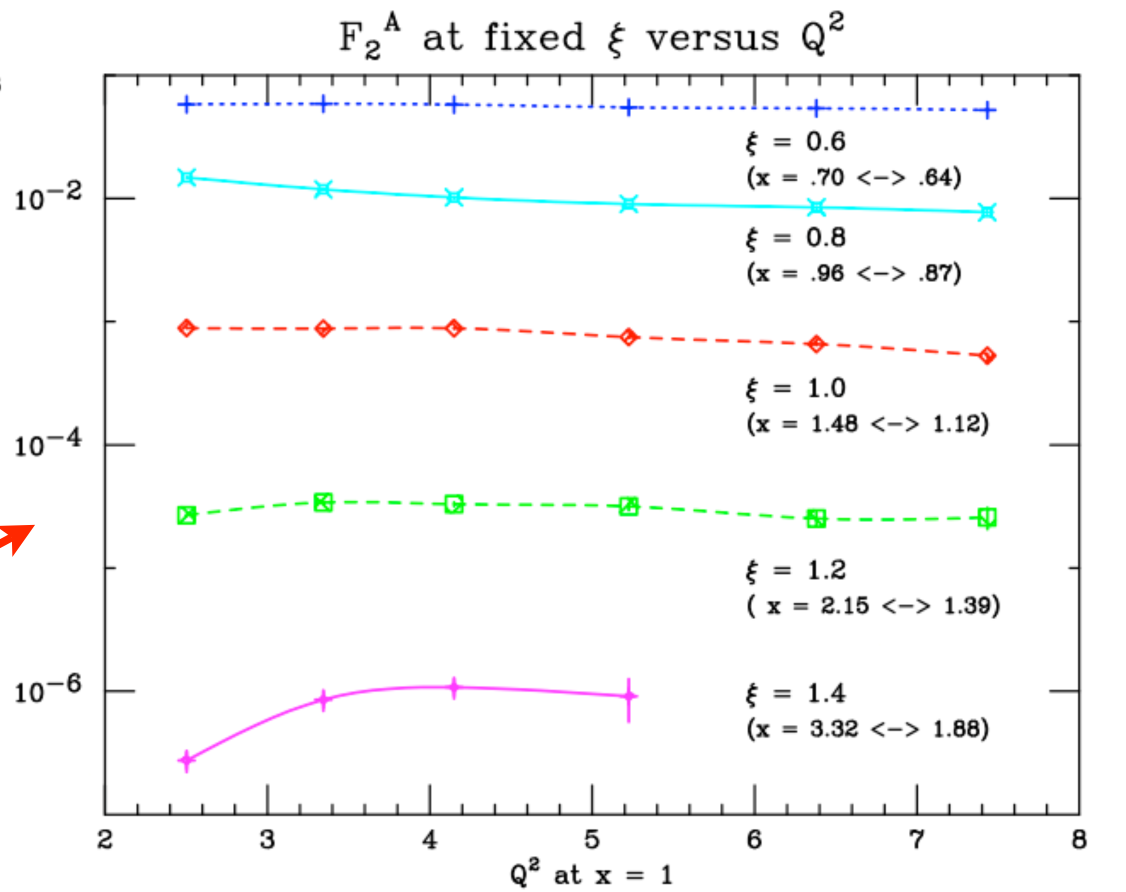


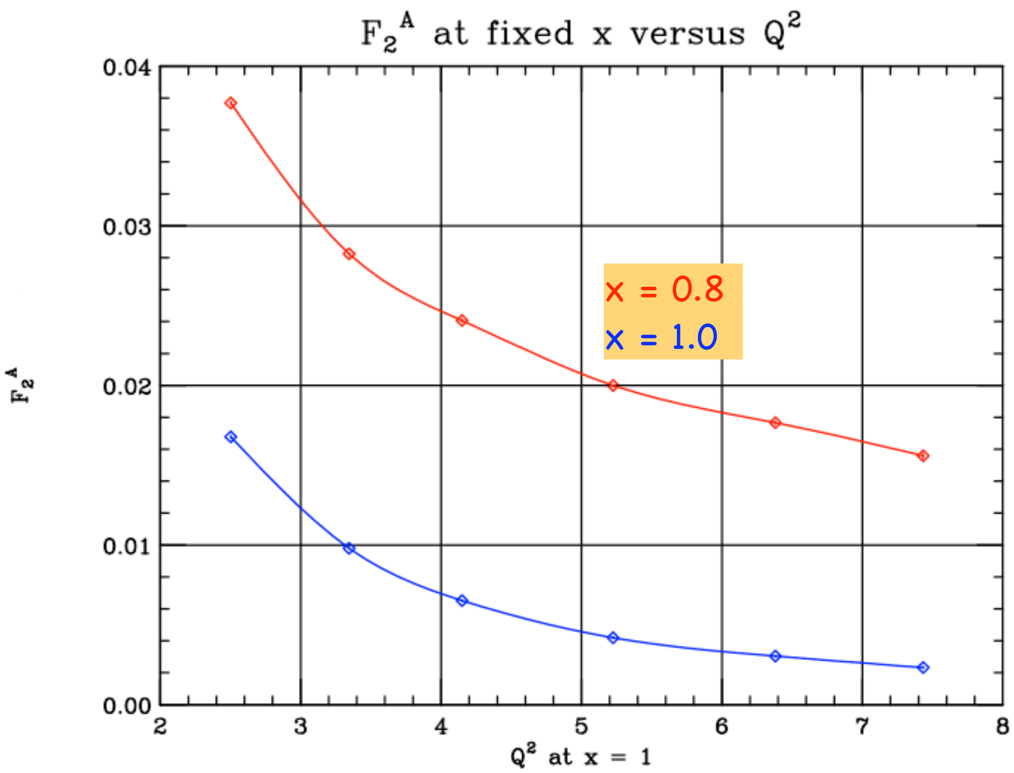
Convergence of F_2^A with Q^2 at fixed x and ξ

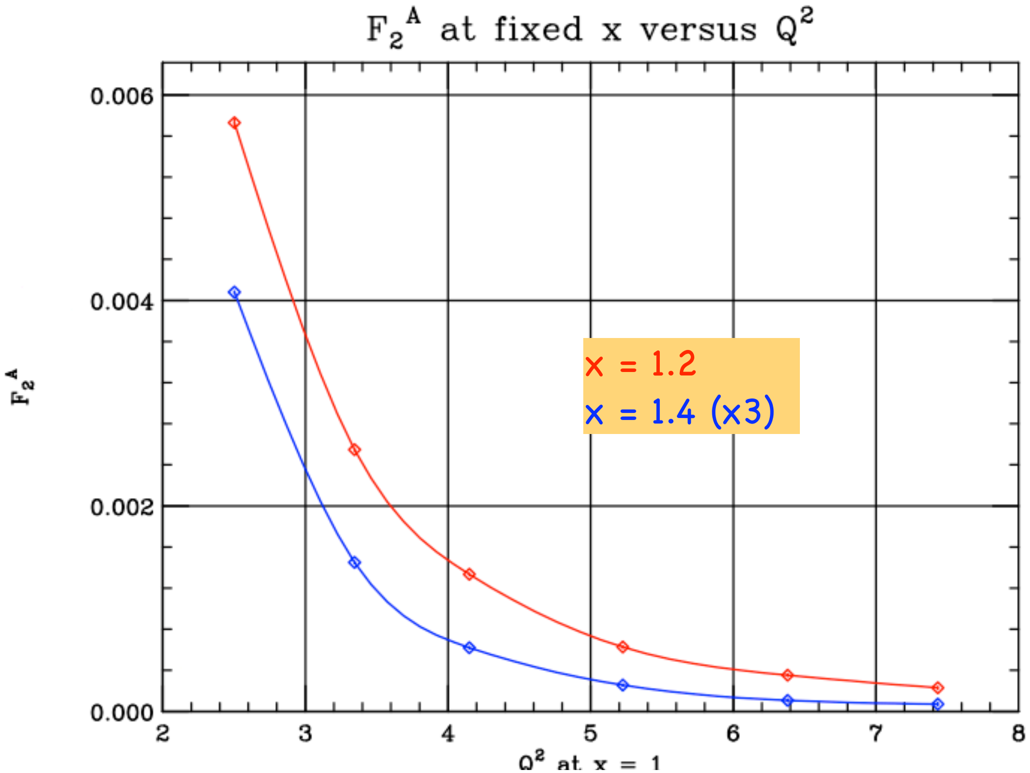


fixed x

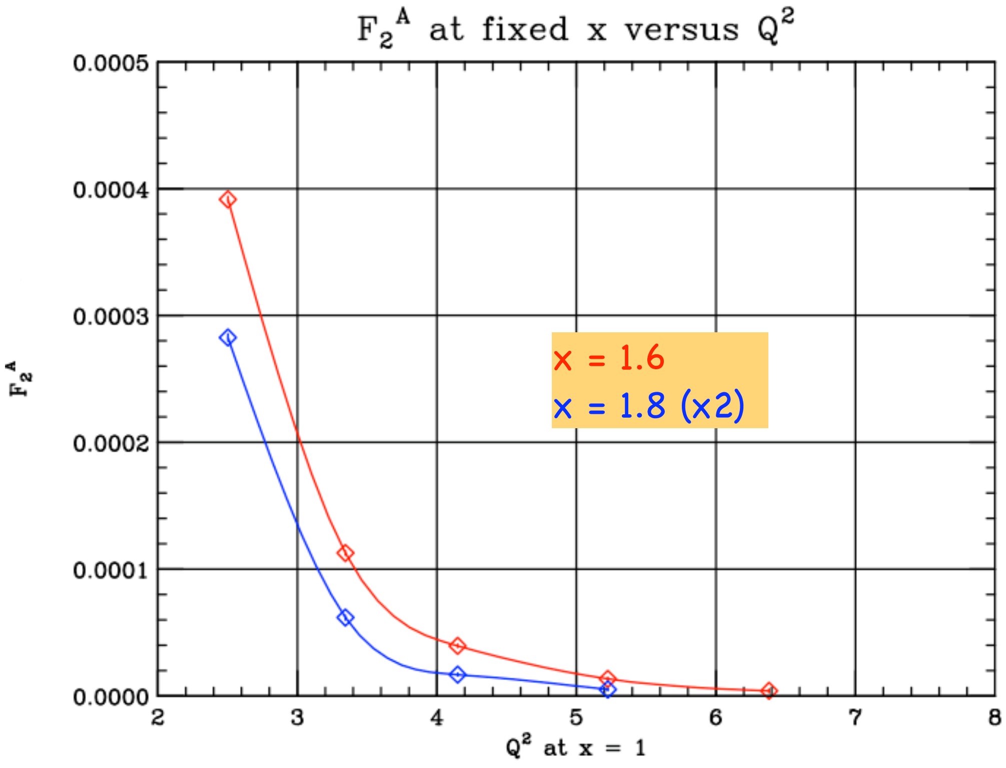
fixed ξ

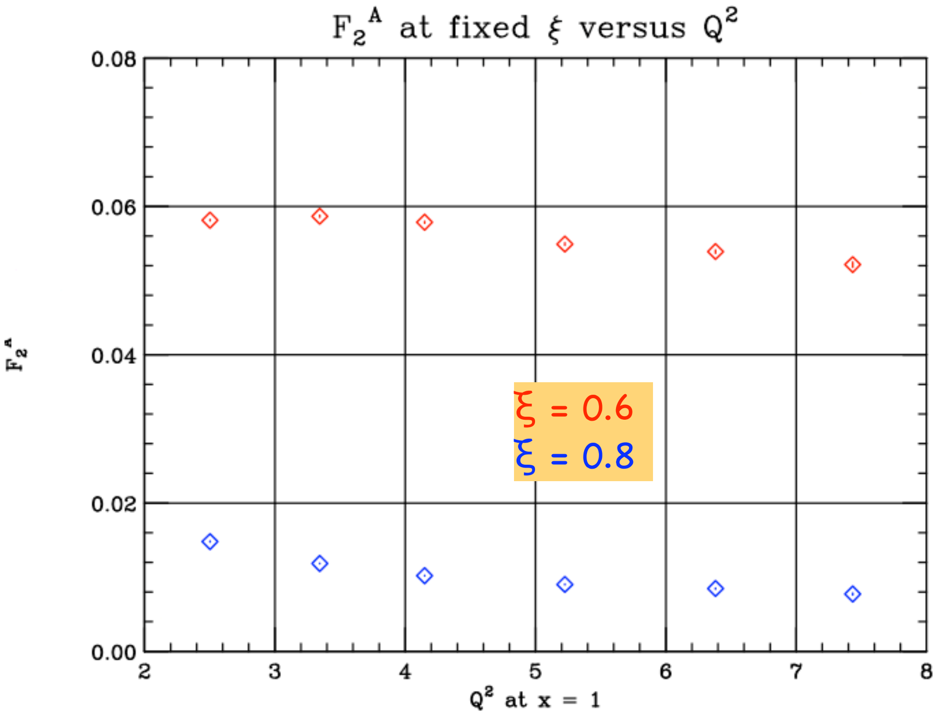


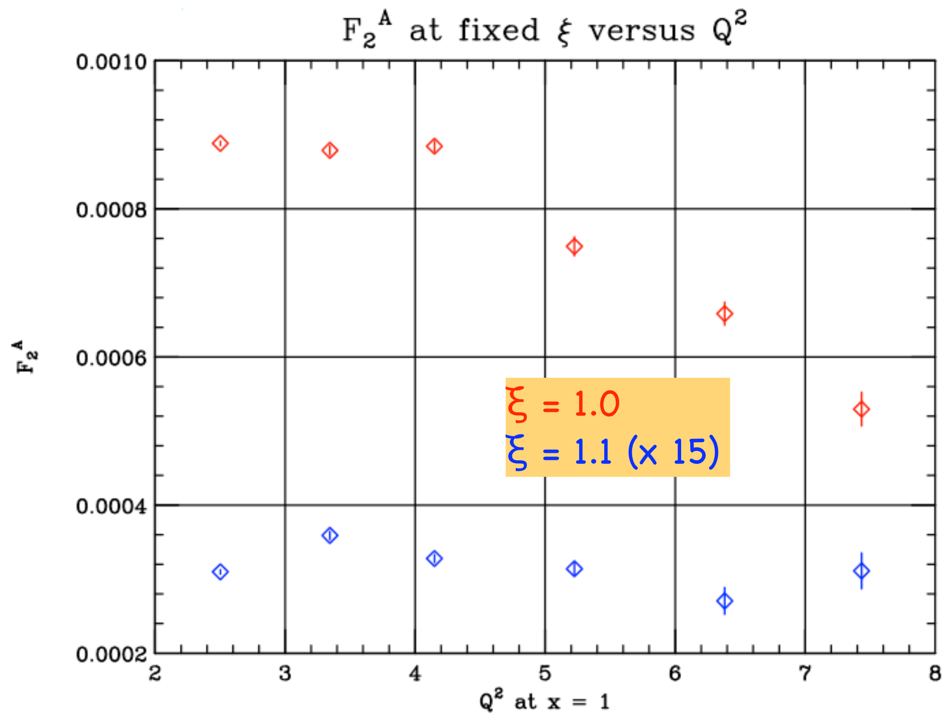




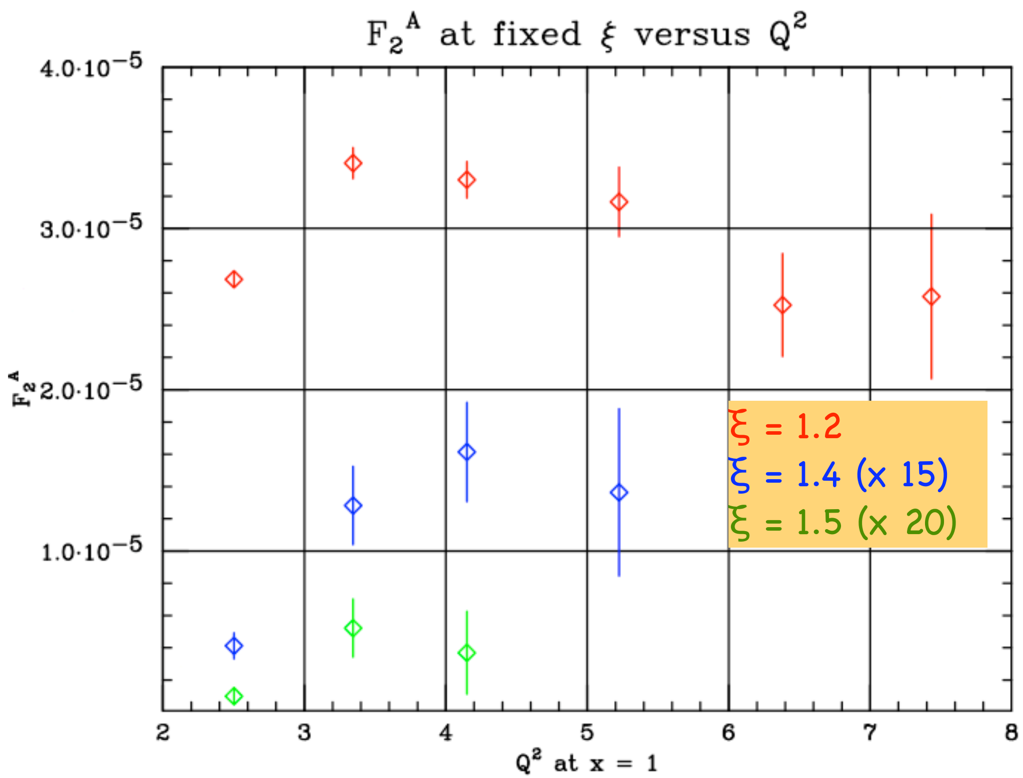
Convergence of F_2^A with Q^2 at fixed x



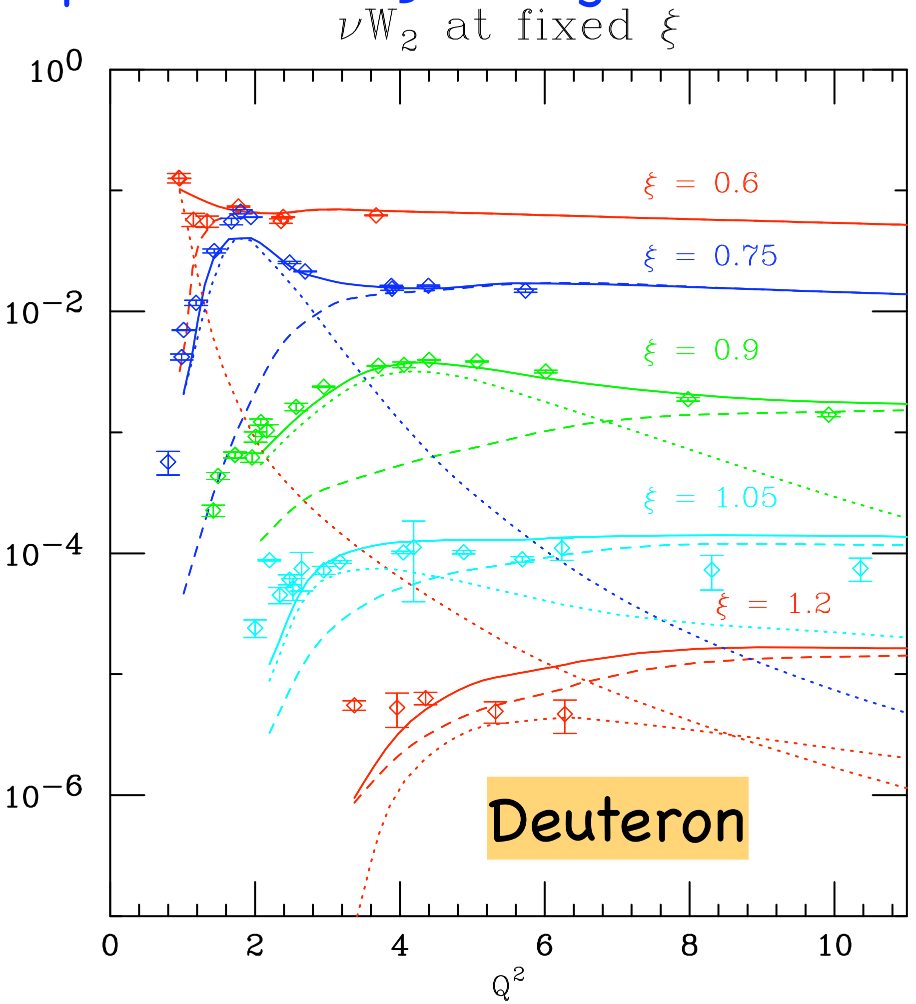


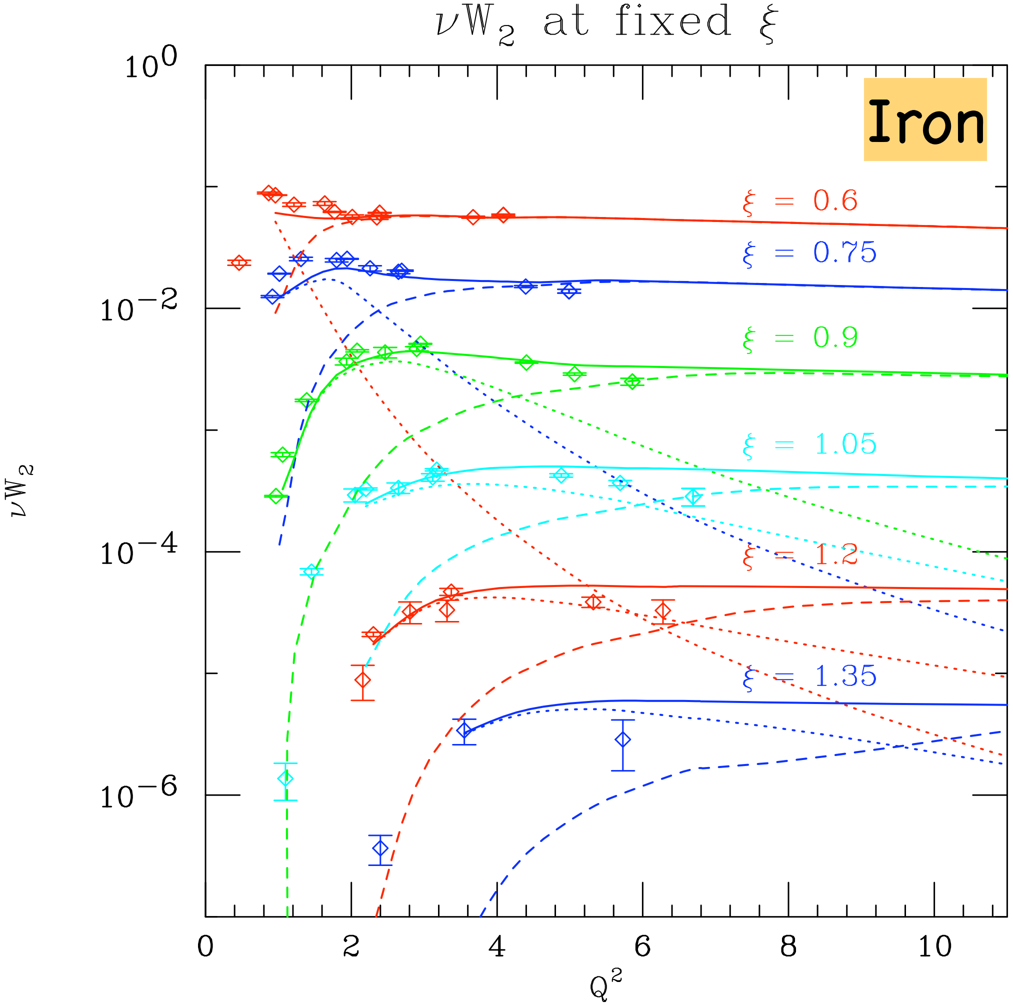


Convergence of F_2^A with Q^2 at fixed ξ



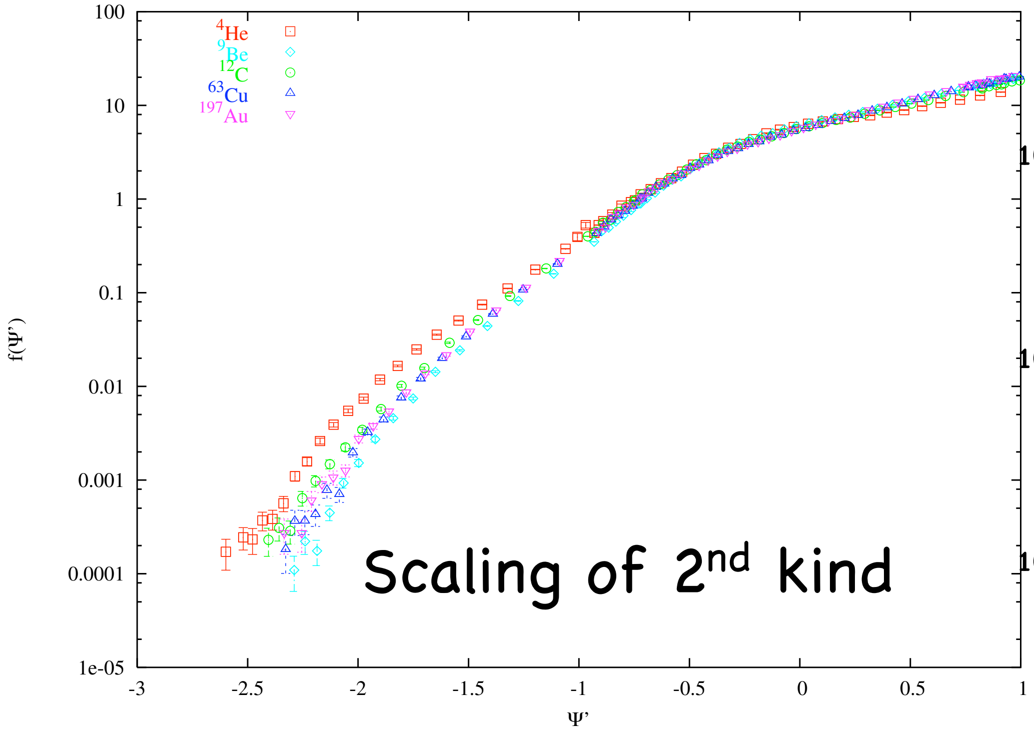
Using a y-scaling model for qes and a convolution of DIS with n(k) we can reproduce the ξ scaling DD and I. Sick, Phys.Rev.C69:028501,2004



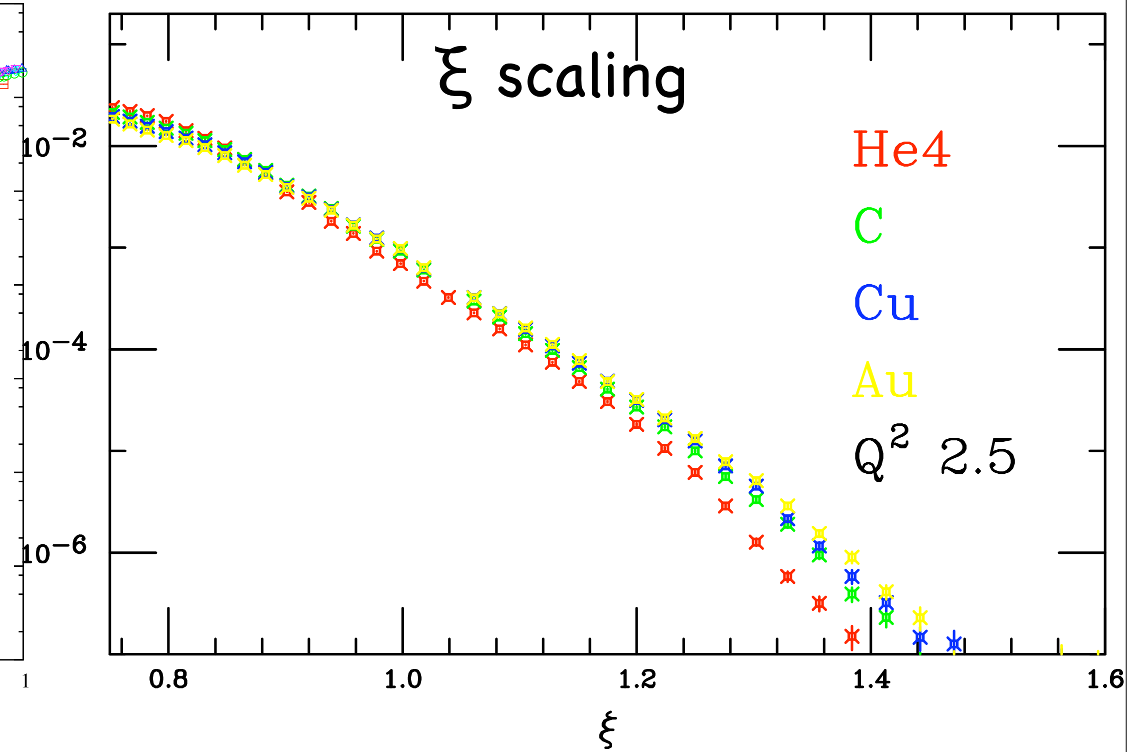


The two dominant contributions to the inclusive cross section behave such that their sum shows a Q^2 independence characteristic of scaling, but separately they do not.

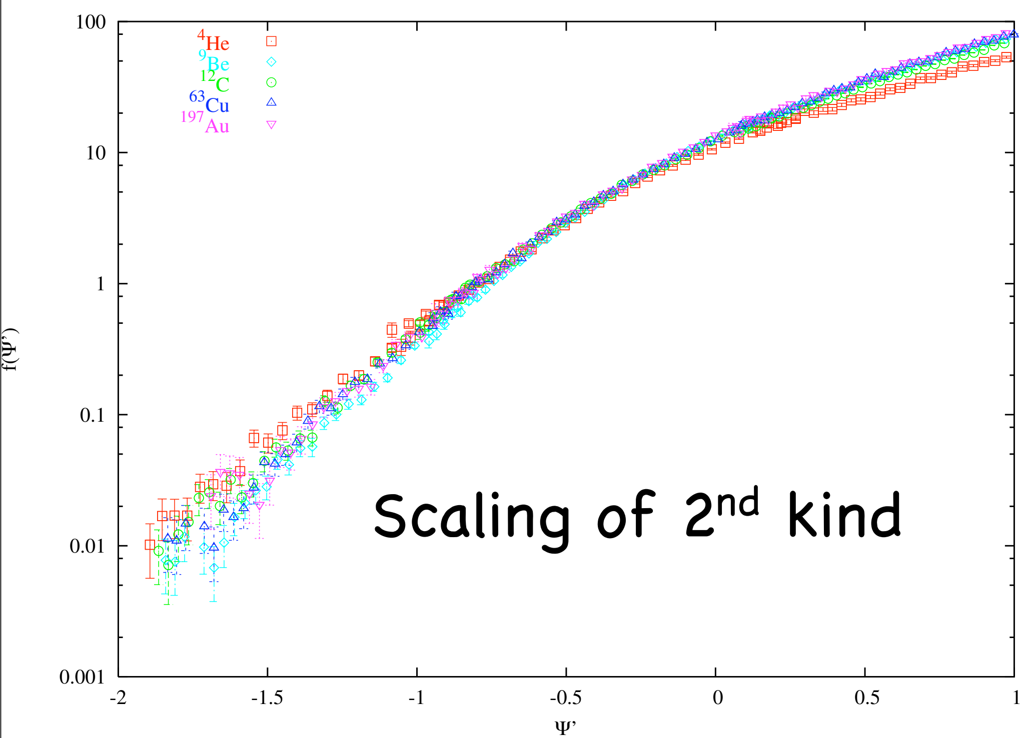
The rapidly varying function are n(k) and the nucleon FF; these have no physical connection.



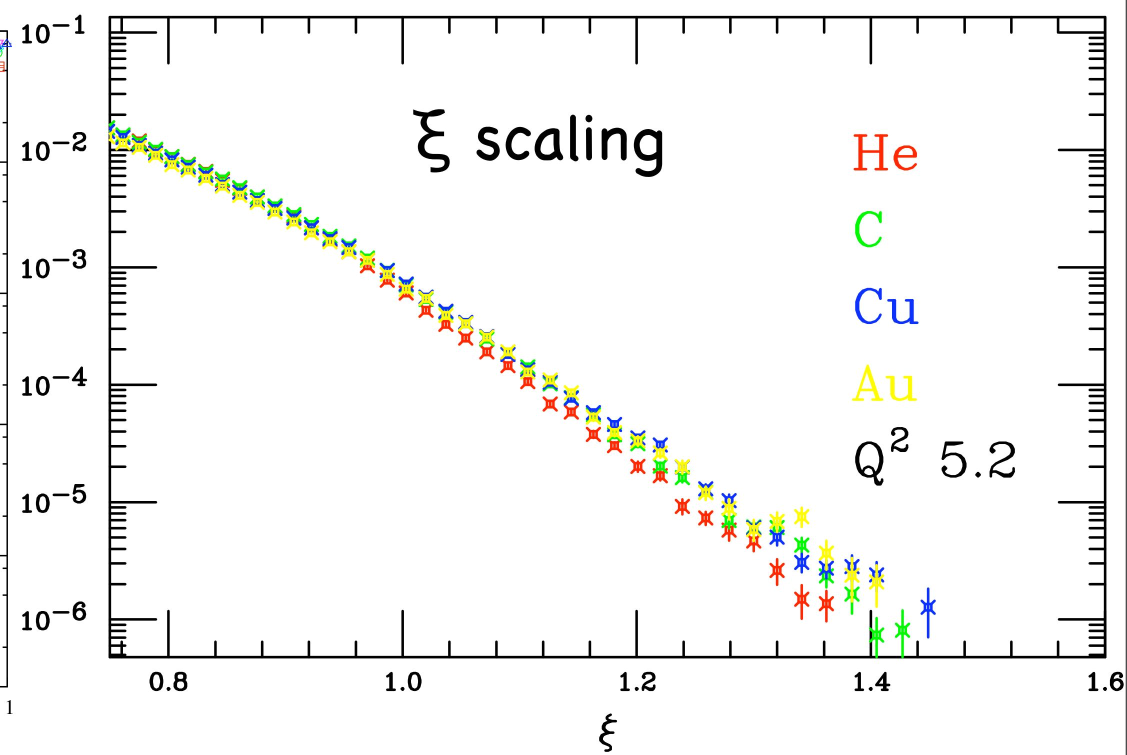
^{4}He
^{9}Be
^{12}C
^{63}Cu
^{197}Au
f(Ψ')
Ψ'
Scaling of 2nd kind



ξ scaling
He4
C
Cu
Au
Q^2 2.5
ξ



^{4}He
^{9}Be
^{12}C
^{63}Cu
^{197}Au
f(Ψ')
Ψ'
Scaling of 2nd kind



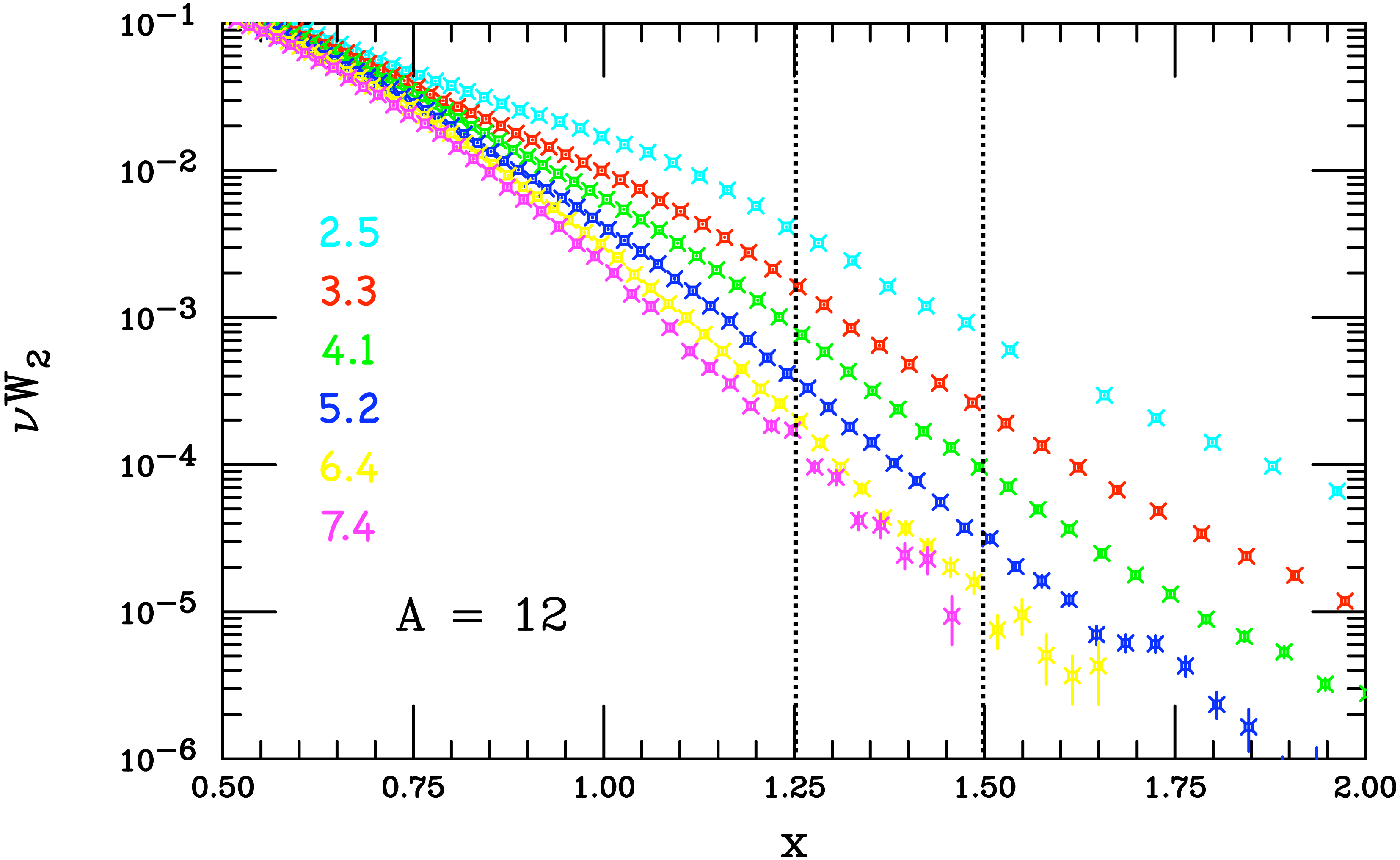
ξ scaling
He
C
Cu
Au
Q^2 5.2
ξ

What is source of Q^2 dependence in F_2^A at fixed x?

- Nucleon form factor
- FSI
- Phase space [x for different Q^2 samples different n(k)]
- TMCs and PDF evolution

Is it possible to extract from our data at some Q_0^2 an F_2 corrected for TMCs and predict F_2 for other Q^2?

What is source of Q^2 dependence in F_2^A at fixed x?



Target Mass Corrections

In OPE

$$F_2^{TMC}(x,Q^2) = \frac{x^2}{\xi^2 r^2} F_2^0(\xi,Q^2) + \frac{6M^2x^3}{Q^2r^4} h_2(\xi,Q^2) + \frac{12M^4x^4}{Q^4r^5} g_2(\xi,Q^2)$$

$$h_2(\xi,Q^2) = \int_\xi^1 du \frac{F_2^0(u,Q^2)}{u^2} \qquad g_2(\xi,Q^2) = \int_\xi^1 dv(v-\xi)\frac{F_2^0(v,Q^2)}{v^2}$$

where F_2^0 is structure function in massless (Bjorken) limit

Allows one to determine target mass corrected structure functions F_2^{TMC} ($M \neq 0$) from massless limit structure functions $F_2^0(Q^2)$.

Georgi, Politzer; DuRujula, Georgi and Politzer
Schienbein et al J.Phys. G. Part. Phys. 35 (2008)

$$\boxed{r = \sqrt{1 + \frac{4x^2M^2}{Q^2}} = \sqrt{1 + \frac{Q^2}{\nu^2}}}$$

Procedure

- Assume data at selected Q_0^2 is entirely leading twist

1. Take F_2^0 to be $F_2^0(\xi, Q^2) = \frac{\xi^2 r^2}{x^2} F_2^{TMC \equiv Data}(x, Q^2)$
2. Fit the F_2^0 with some convenient form
3. Use this to calculate integrals

$$h_2(\xi, Q^2) = \int_\xi^1 du \frac{F_2^0(u, Q^2)}{u^2} \qquad g_2(\xi, Q^2) = \int_\xi^1 dv (v - \xi) \frac{F_2^0(v, Q^2)}{v^2}$$

4. Calculate F_2^0 again by

$$F_2^0(\xi, Q^2) = \frac{\xi^2 r^2}{x^2} \left[F_2^{TMC}(x, Q^2) - \frac{6M^2 x^3}{Q^2 r^4} h_2(\xi, Q^2) - \frac{12 M^4 x^4}{Q^4 r^5} g_2(\xi, Q^2) \right]$$

5. Go back to 2 until F_2^0 quits changing

Procedure, continued

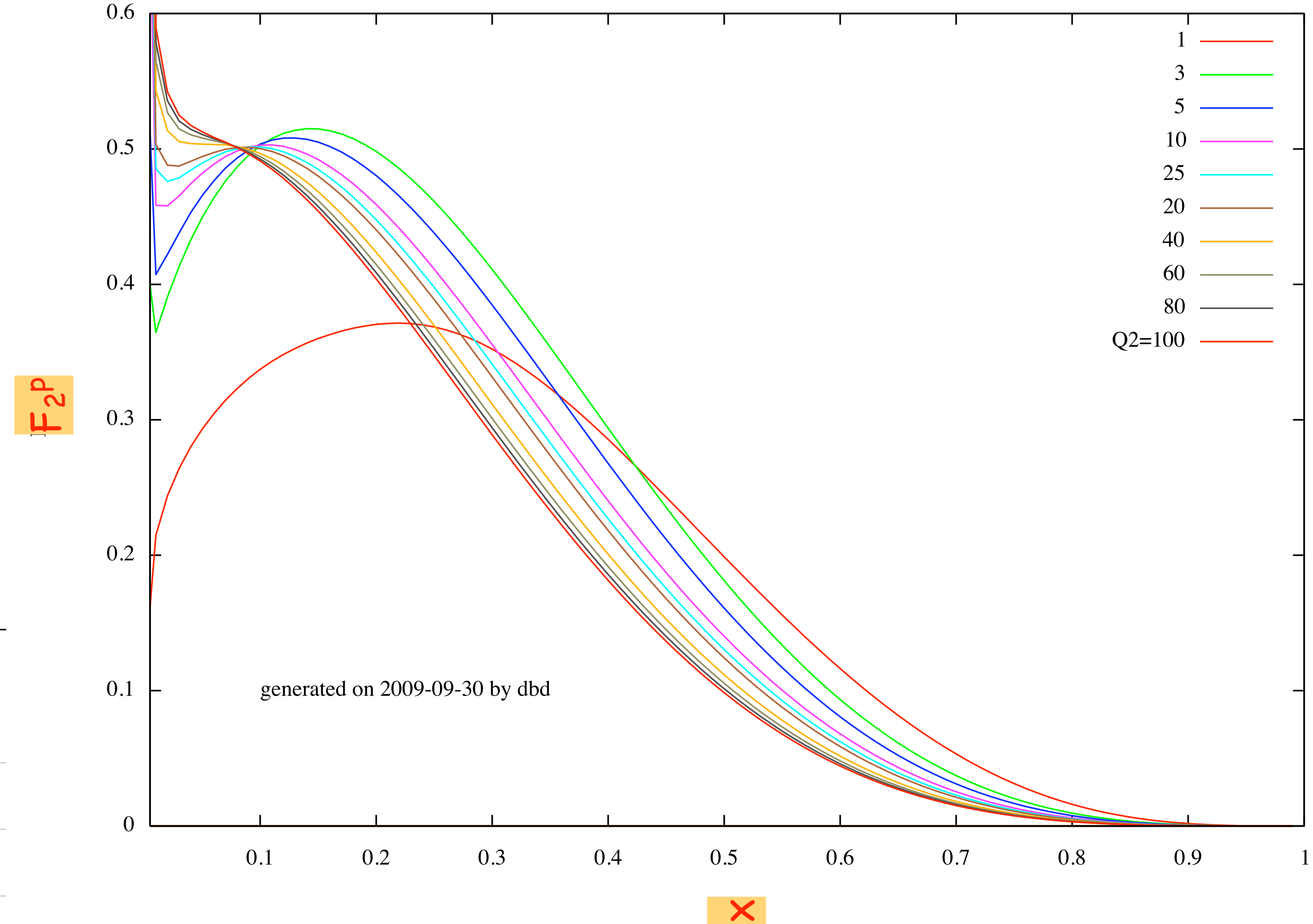
- Evolve fit to data at Q_0^2 (up or down) to other Q^2 (using slopes of $d(\ln F_2)/d(\ln Q^2)$ extrapolated into the region $x > 1$)
- Apply target mass corrections (TMC) and compare with other (higher or lower) Q^2 data

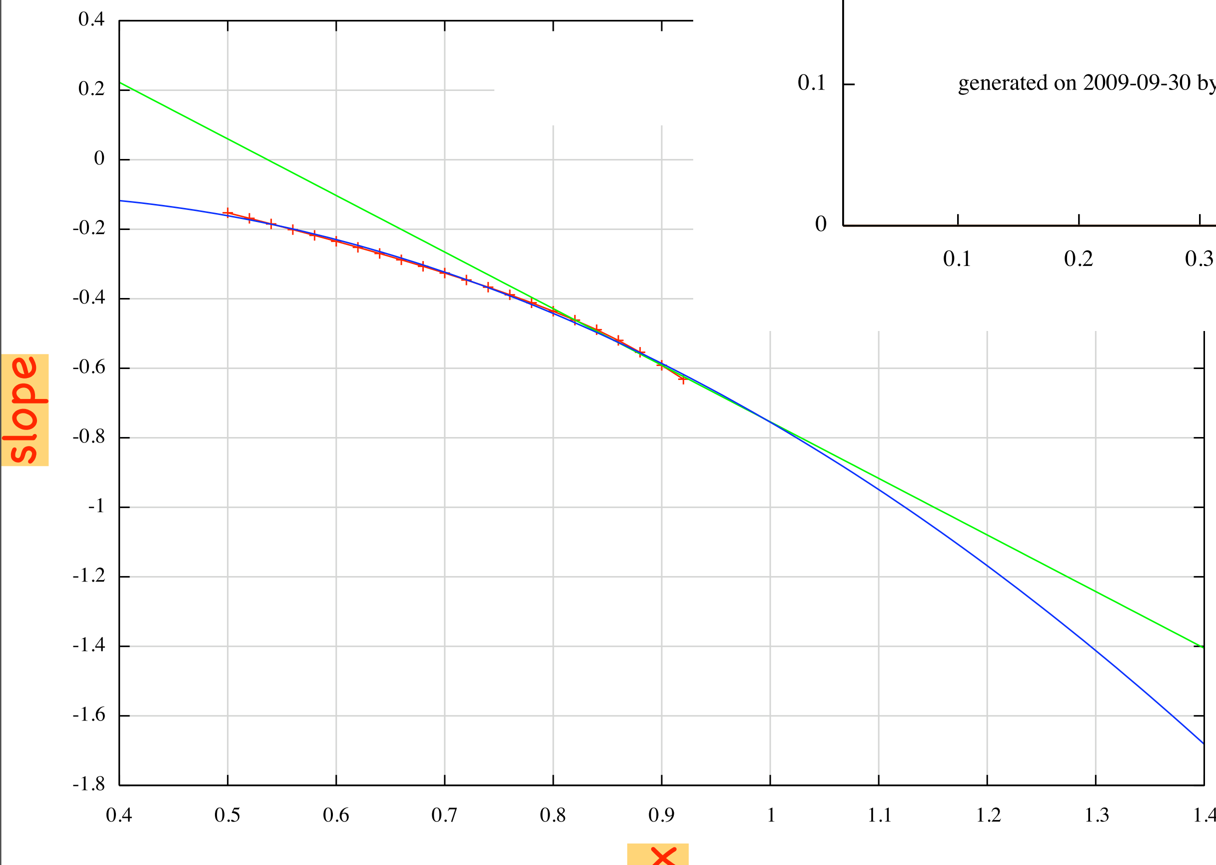
$$F_2^{TMC}(x, Q^2) = \frac{x^2}{\xi^2 r^2} F_2^0(\xi, Q^2) + \frac{6M^2 x^3}{Q^2 r^4} h_2(\xi, Q^2) + \frac{12 M^4 x^4}{Q^4 r^5} g_2(\xi, Q^2)$$

$$h_2(\xi, Q^2) = \int_\xi^1 du \frac{F_2^0(u, Q^2)}{u^2} \qquad g_2(\xi, Q^2) = \int_\xi^1 dv (v - \xi) \frac{F_2^0(v, Q^2)}{v^2}$$

Leaps of Faith

That slopes of d(lnF2)/d(lnQ2) can be extrapolated into the region x > 1)



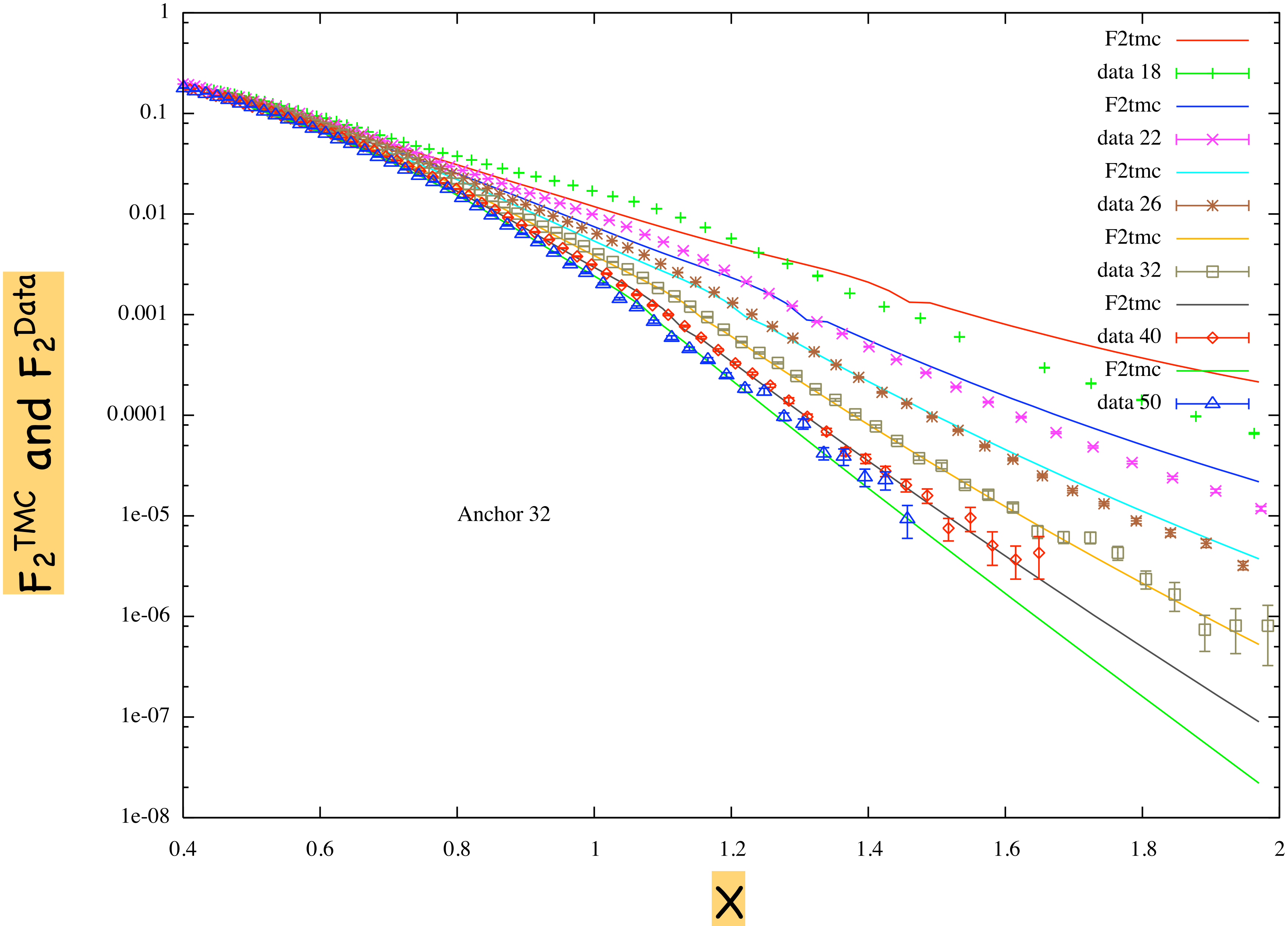


That the anchor Q^2 spectra is, in fact leading twist.

Integrals at fixed Q^2 can be replaced with integrals over variable Q^2

Results

Starting point is 32 degree data, $Q^2 = 5.2$ at $x = 1$



Q^2 at $x = 1$

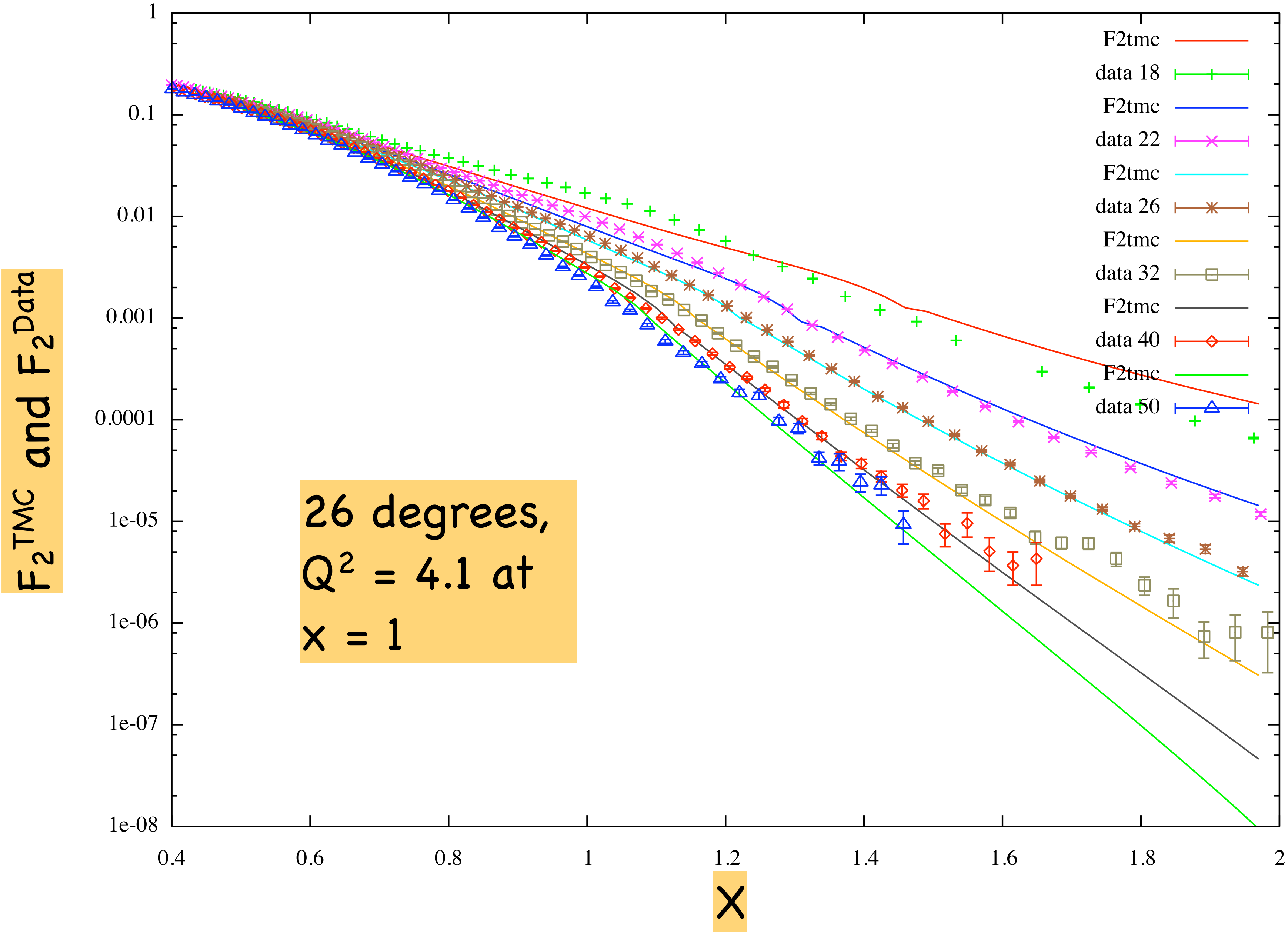
2.5
3.3
4.1
5.2
6.4
7.4

Q^2 at x_{max}

3.0
4.3
5.4
6.9
8.5
9.6

Results

Similar results for other starting Q^2s

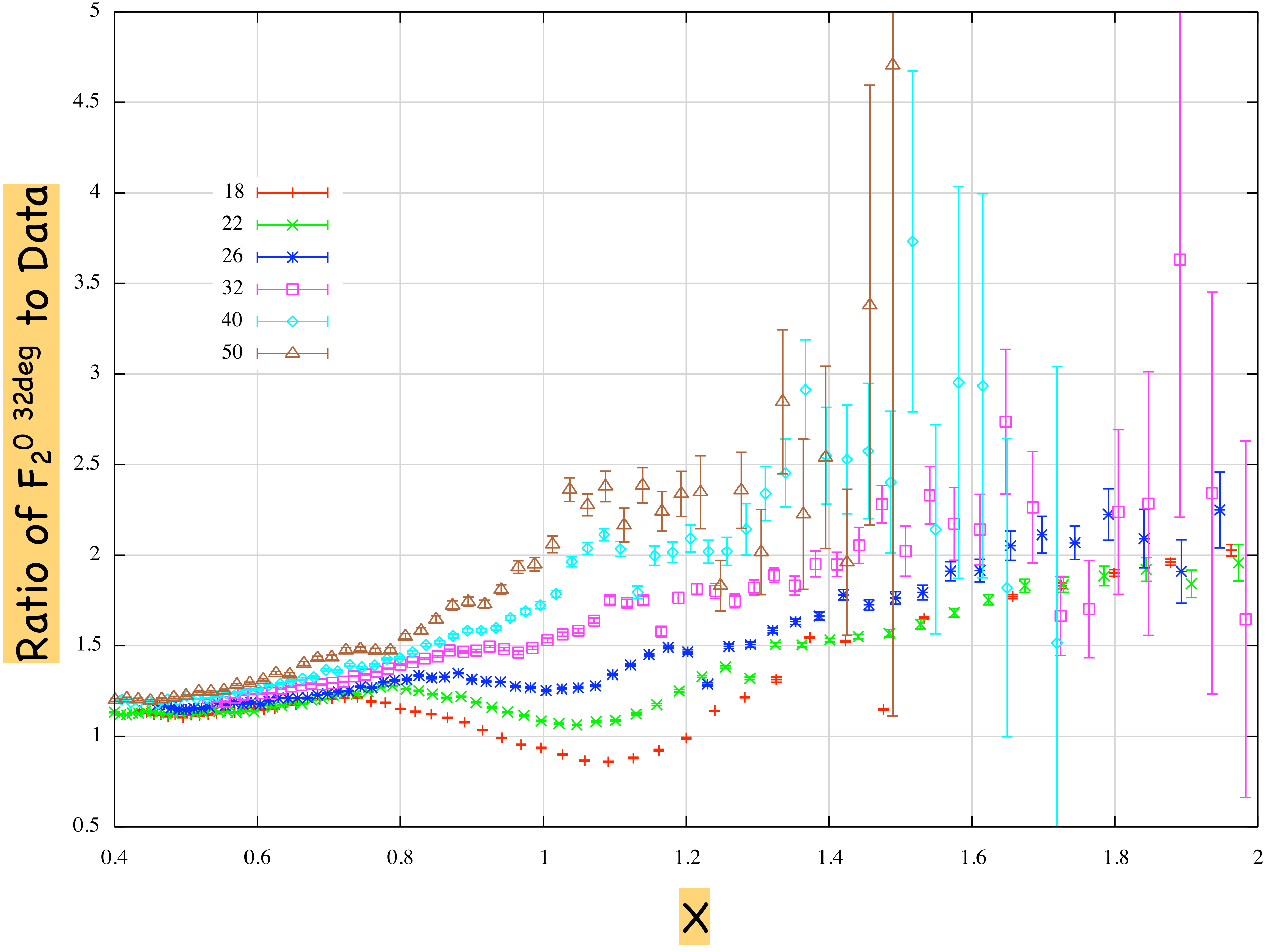


Q^2 at x = 1

2.5
3.3
4.1
5.2
6.4
7.4

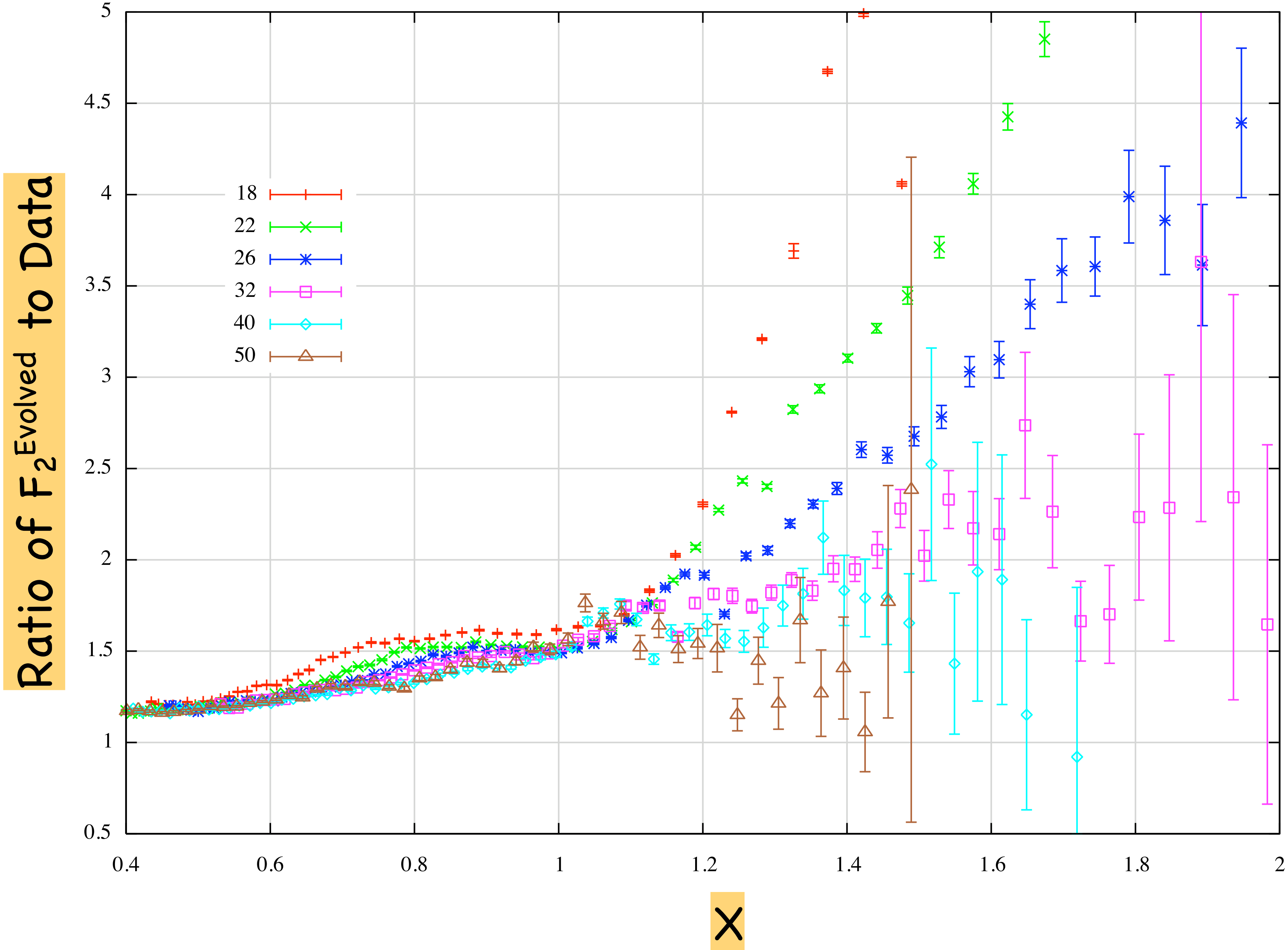
Q^2 at x_{max}

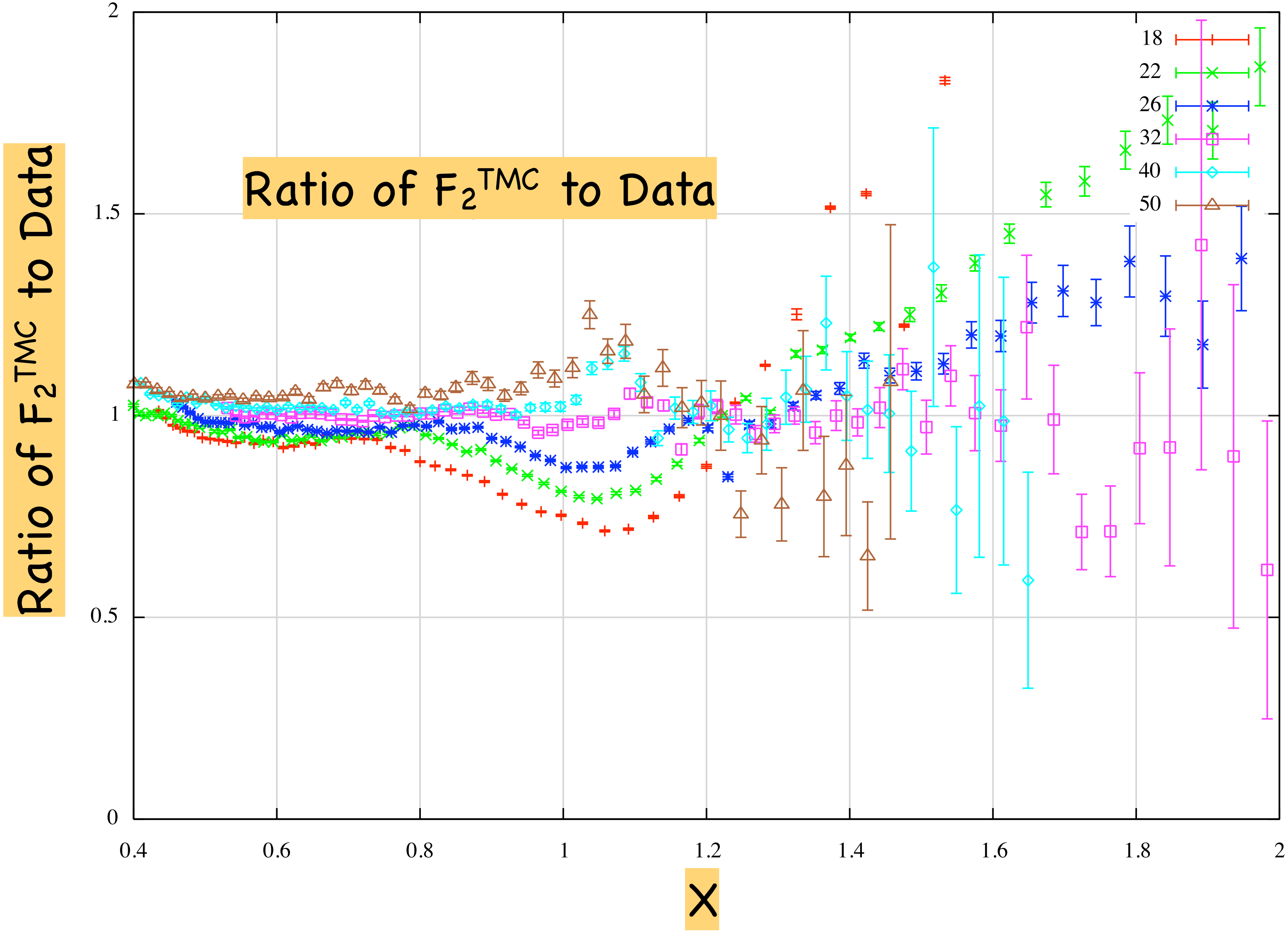
3.0
4.3
5.4
6.9
8.5
9.6



Ratio of F_2^0 32deg to Data
X
18
22
26
32
40
50
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

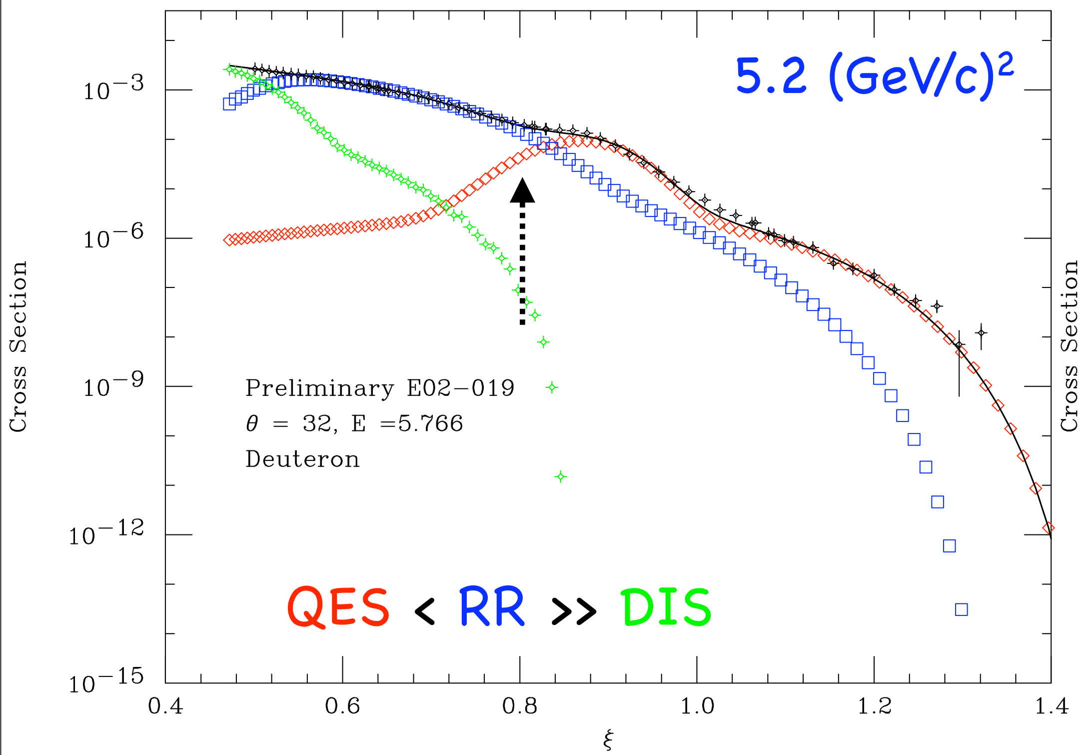
Ratio of $F_2^{Evolved}$ to Data

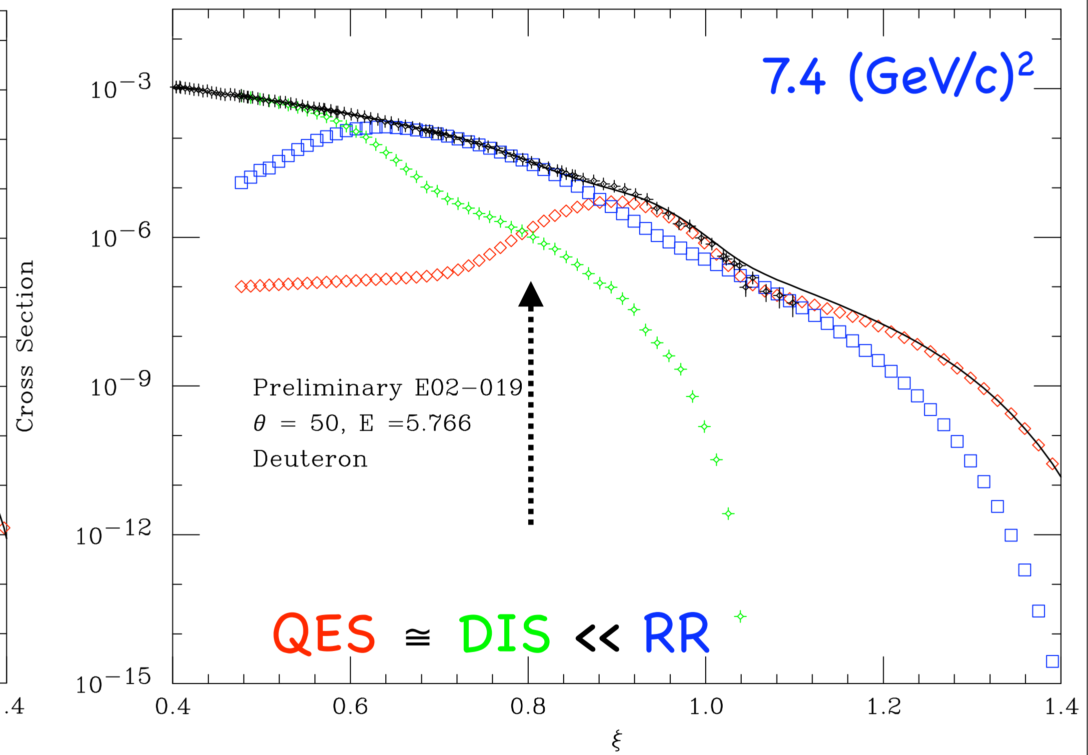




Currently unrefined but it appears that most of the Q^2 dependence can be understood

Approach to Scaling (Deuteron)





Convolution model

QES

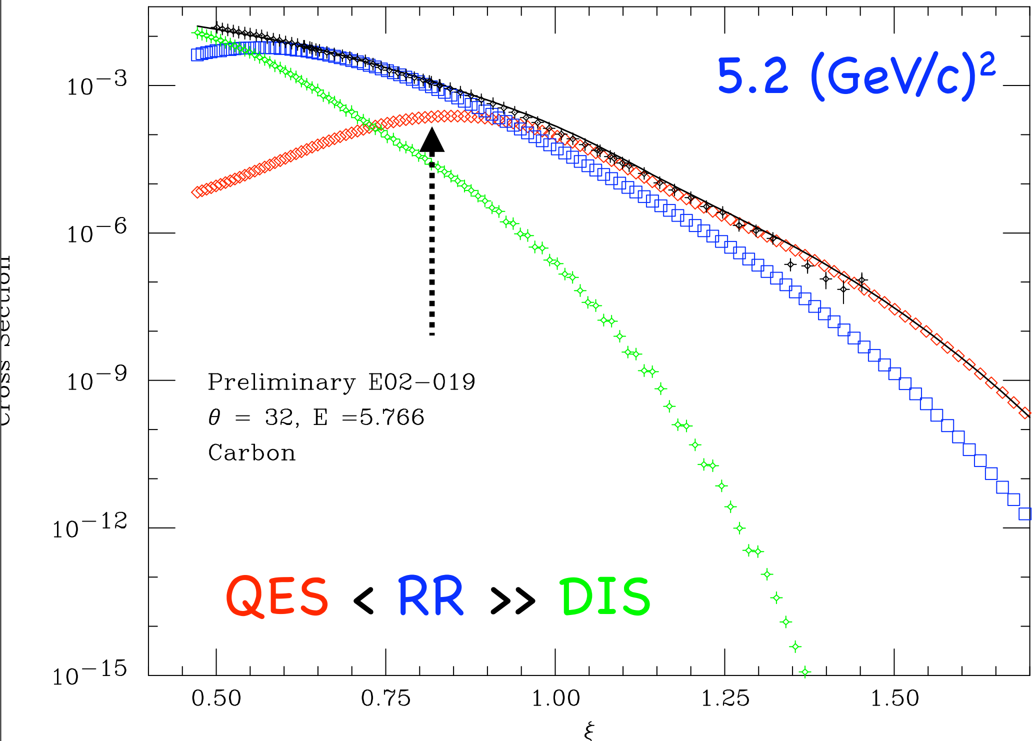
RR ($W^2 < 4$)

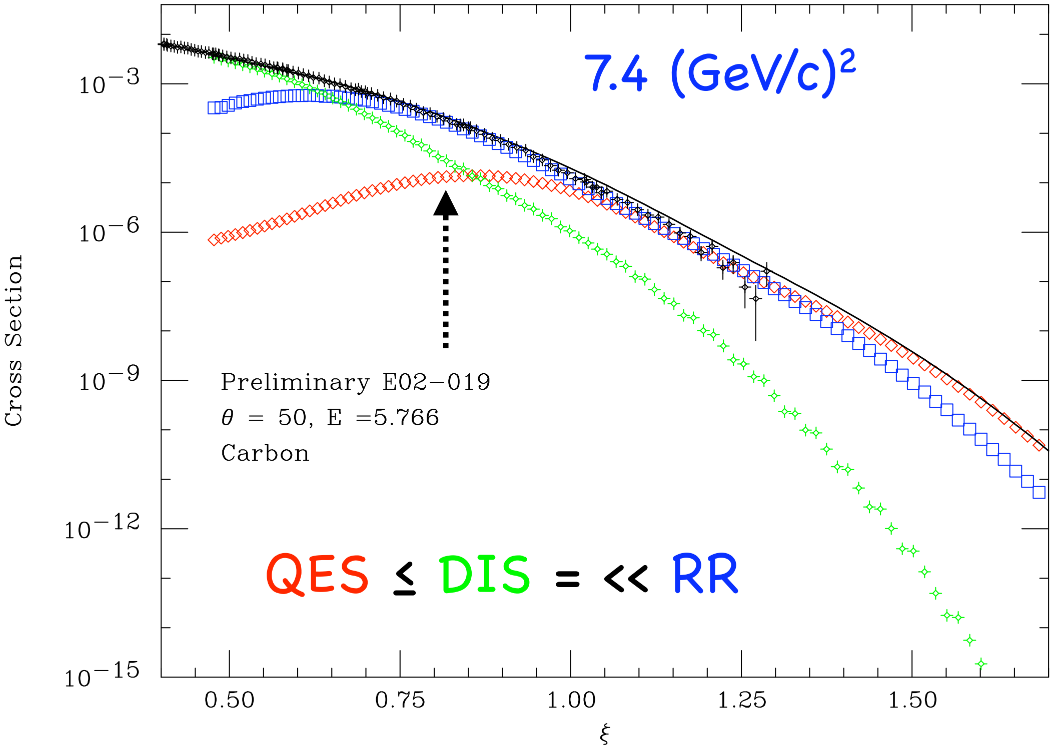
DIS ($W^2 > 4$)

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 ($W^2 > 4$)

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Quark distributions at x > 1

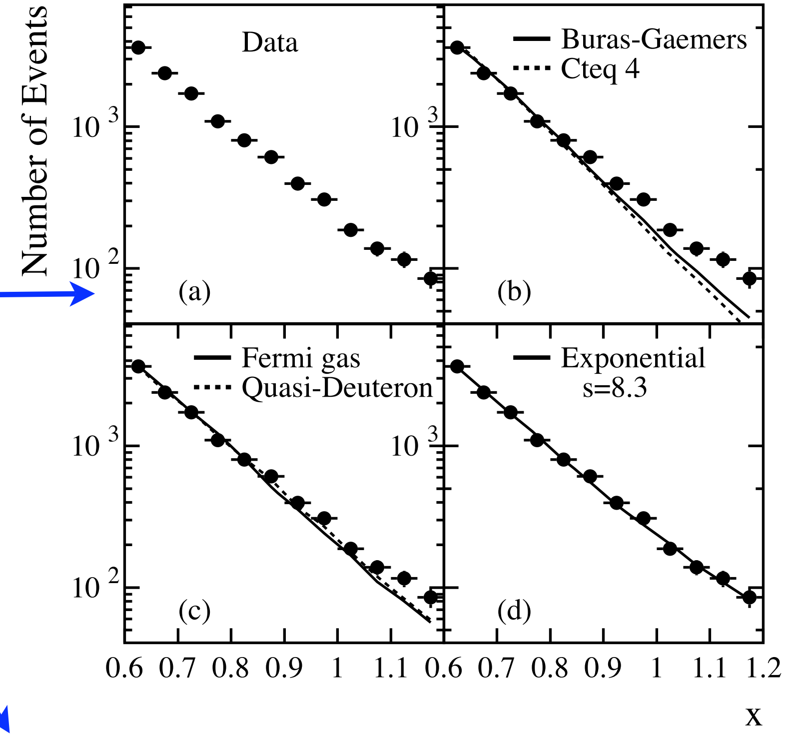
Two measurements (very high Q^2) exist so far:

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

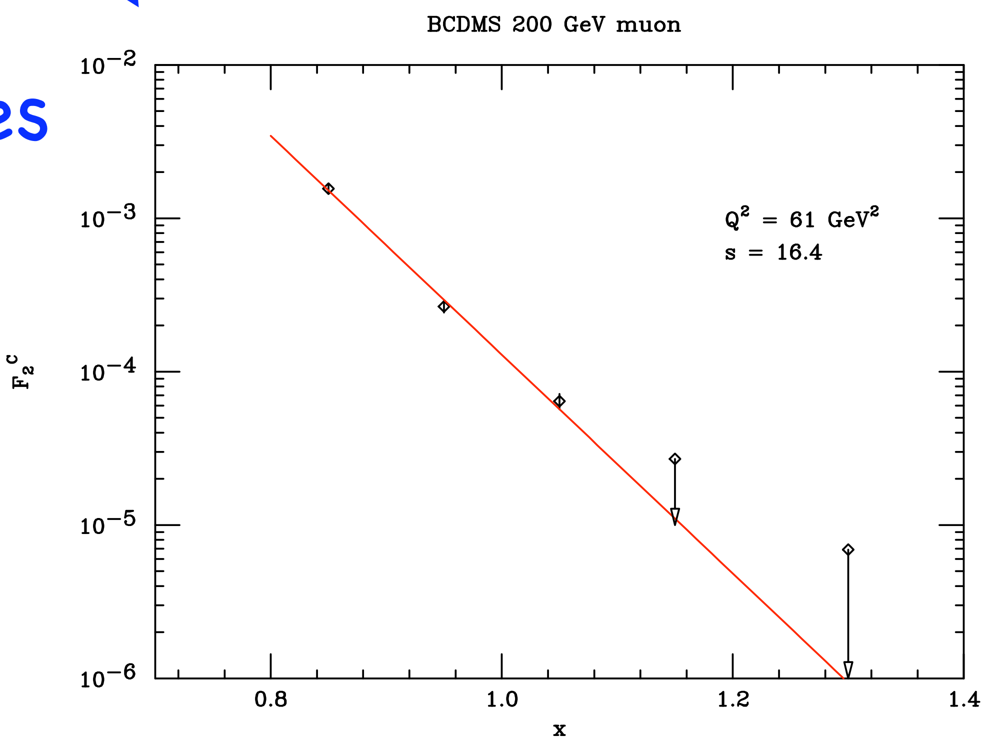
BCDMS (μ-Fe): $F_2(x) \propto e^{-sx}$ s = 16

Limited x range, poor resolution

Limited x range, low statistics



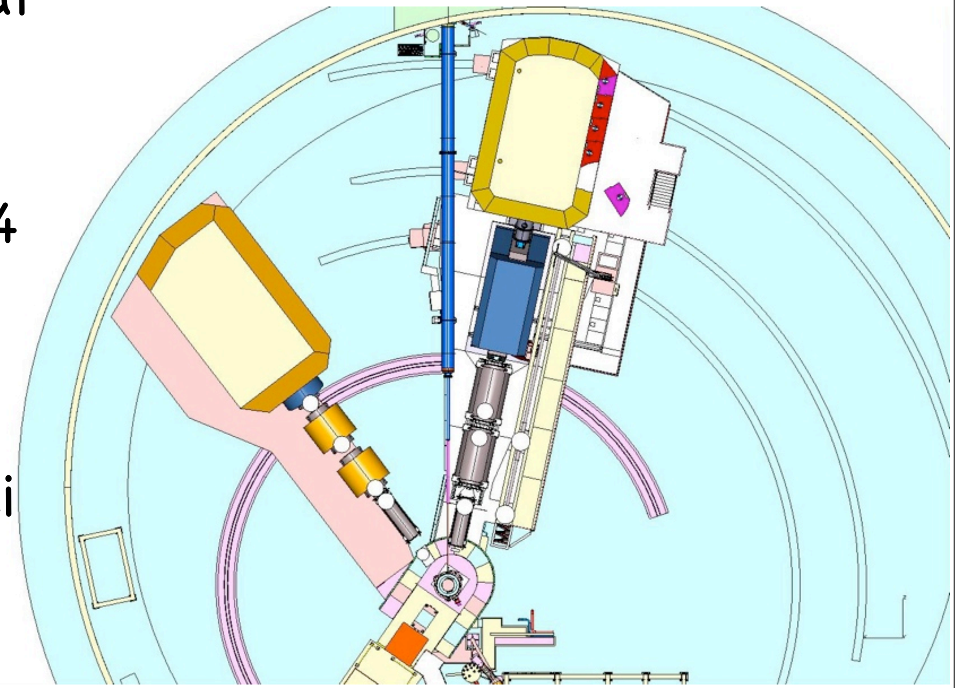
Jlab data fitted to e^{-sx} gives back s = 16±0.5 (over all Q^2).



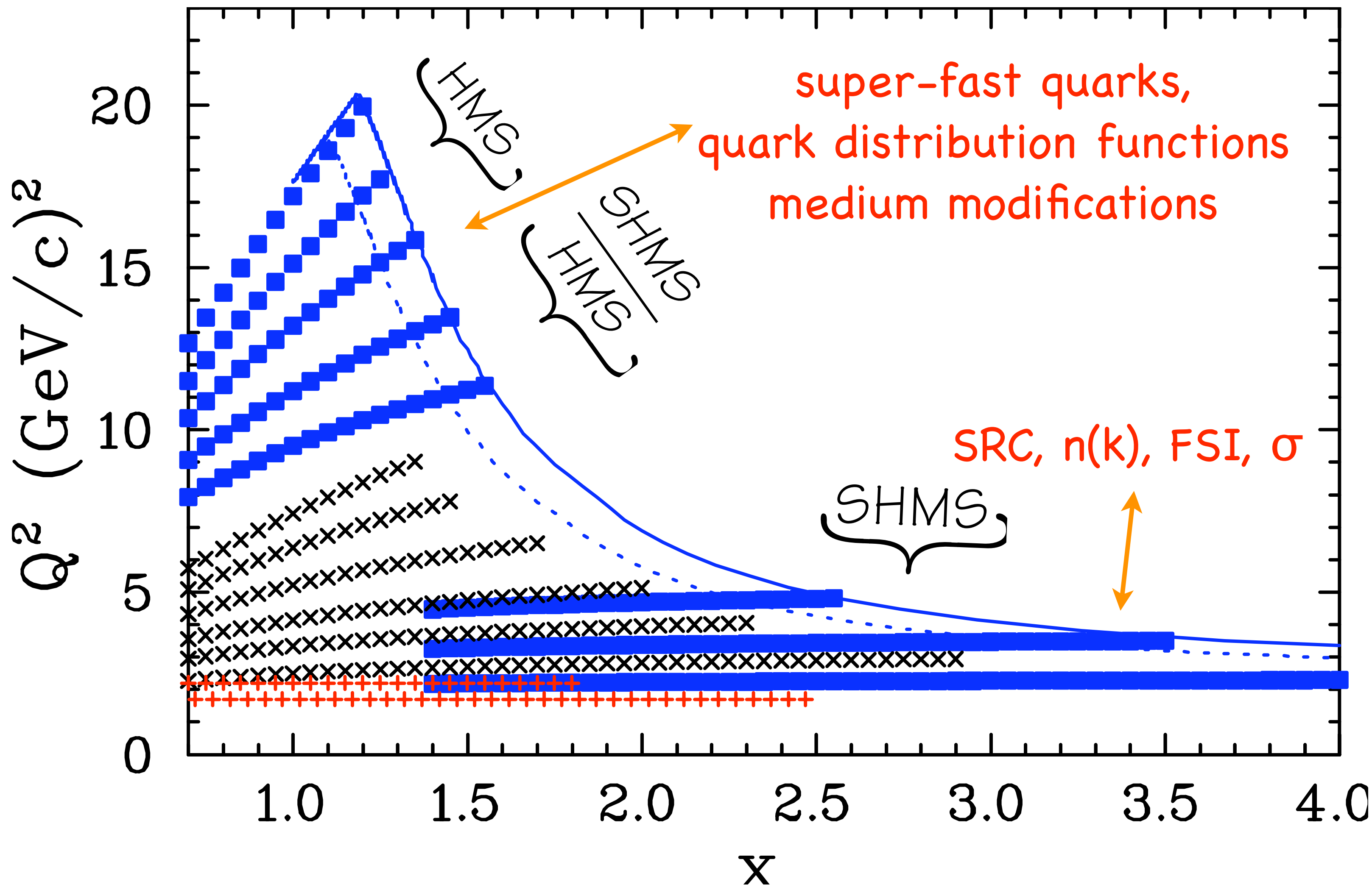
Similar slopes for BCDMS data at Q^2 = 85 and 150

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



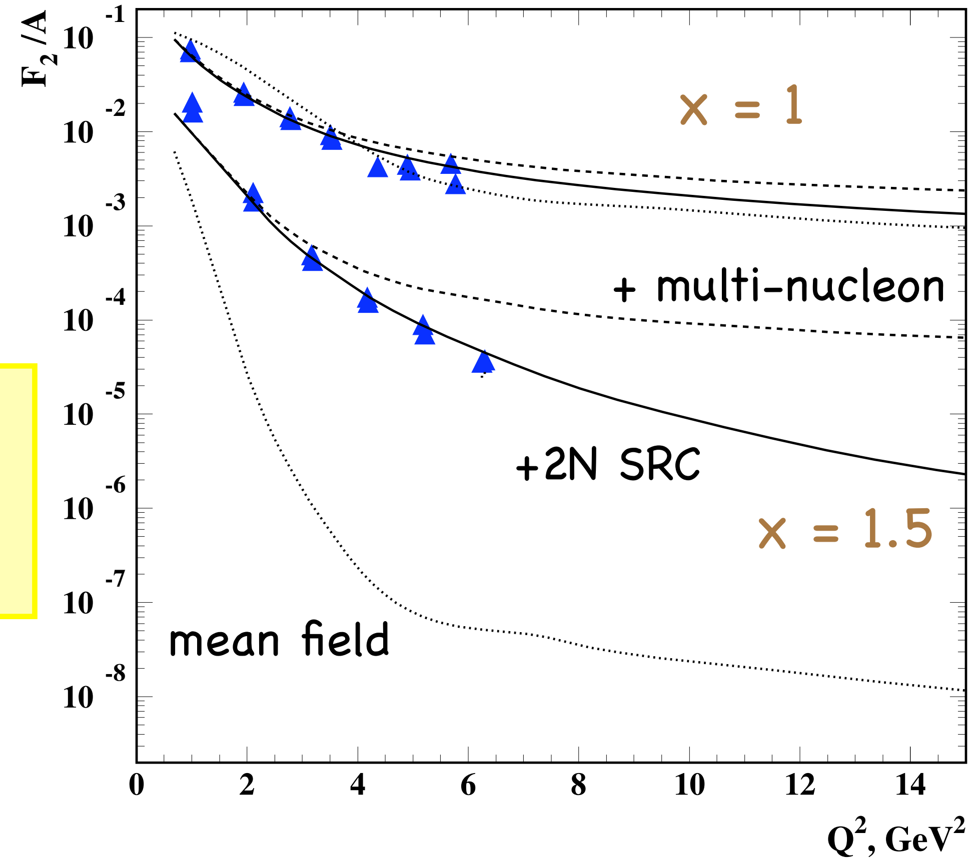
Kinematic range to be explored



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

Sensitivity to SRC increase with Q^2 and x

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



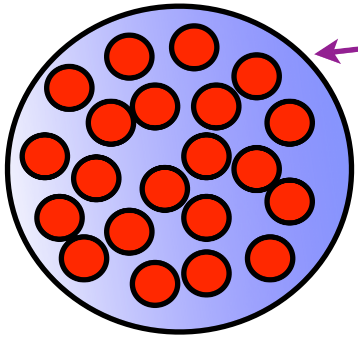
Dotted = mean field approx.
Solid = +2N SRCs.
Dashed = +multi-nucleon.

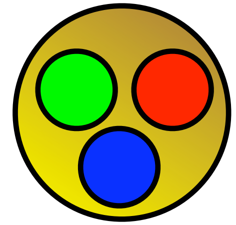
11 GeV can reach Q^2= 20(13) GeV^2 at x = 1.3(1.5)

- very sensitive, especially at higher x values

Medium Modifications generated by high density configurations

Gold nucleus





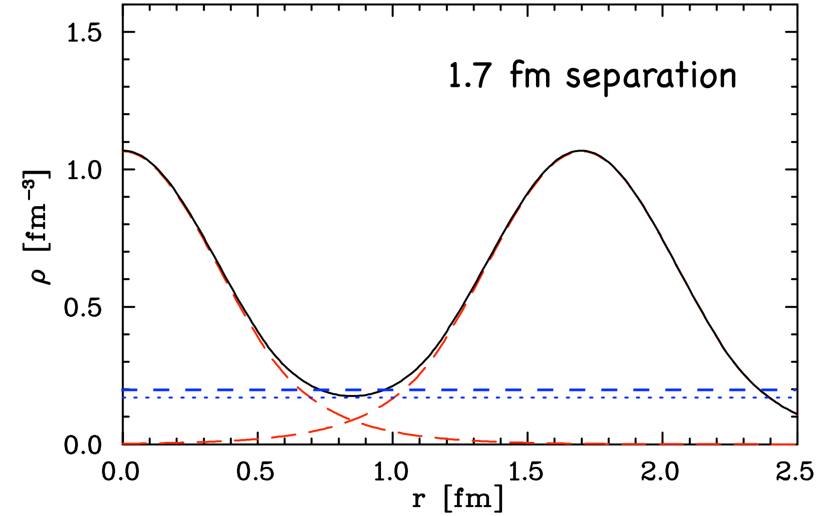
$R = 1.2A^{1/3}$

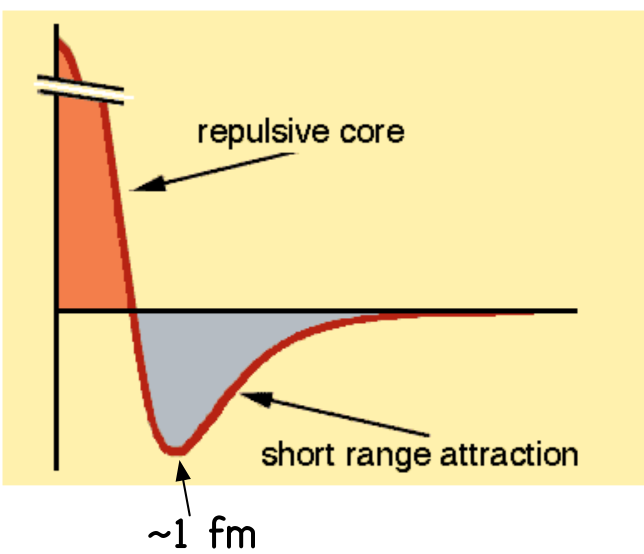
$Volume = \frac{4}{3}\pi R^3 \simeq 1400 fm^3$

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

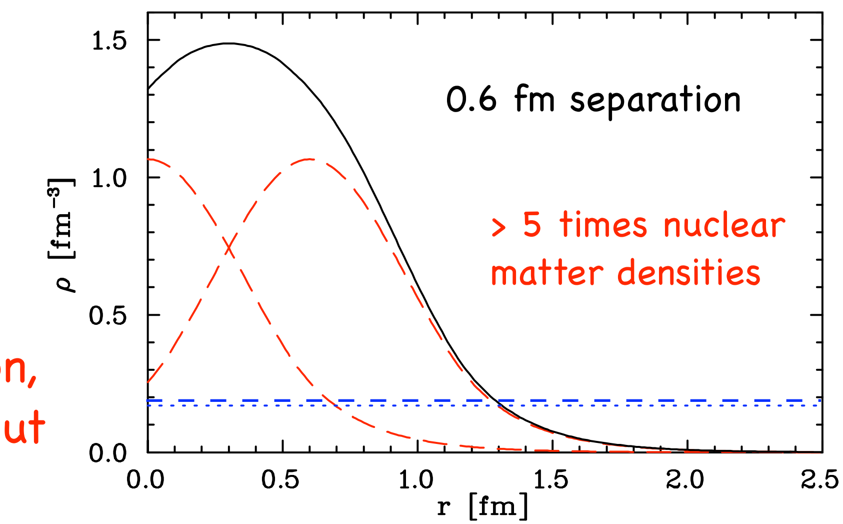
197 times 4.2 fm^3 ≈ 830 fm^3

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





Nucleon separation is limited by the short range repulsive core



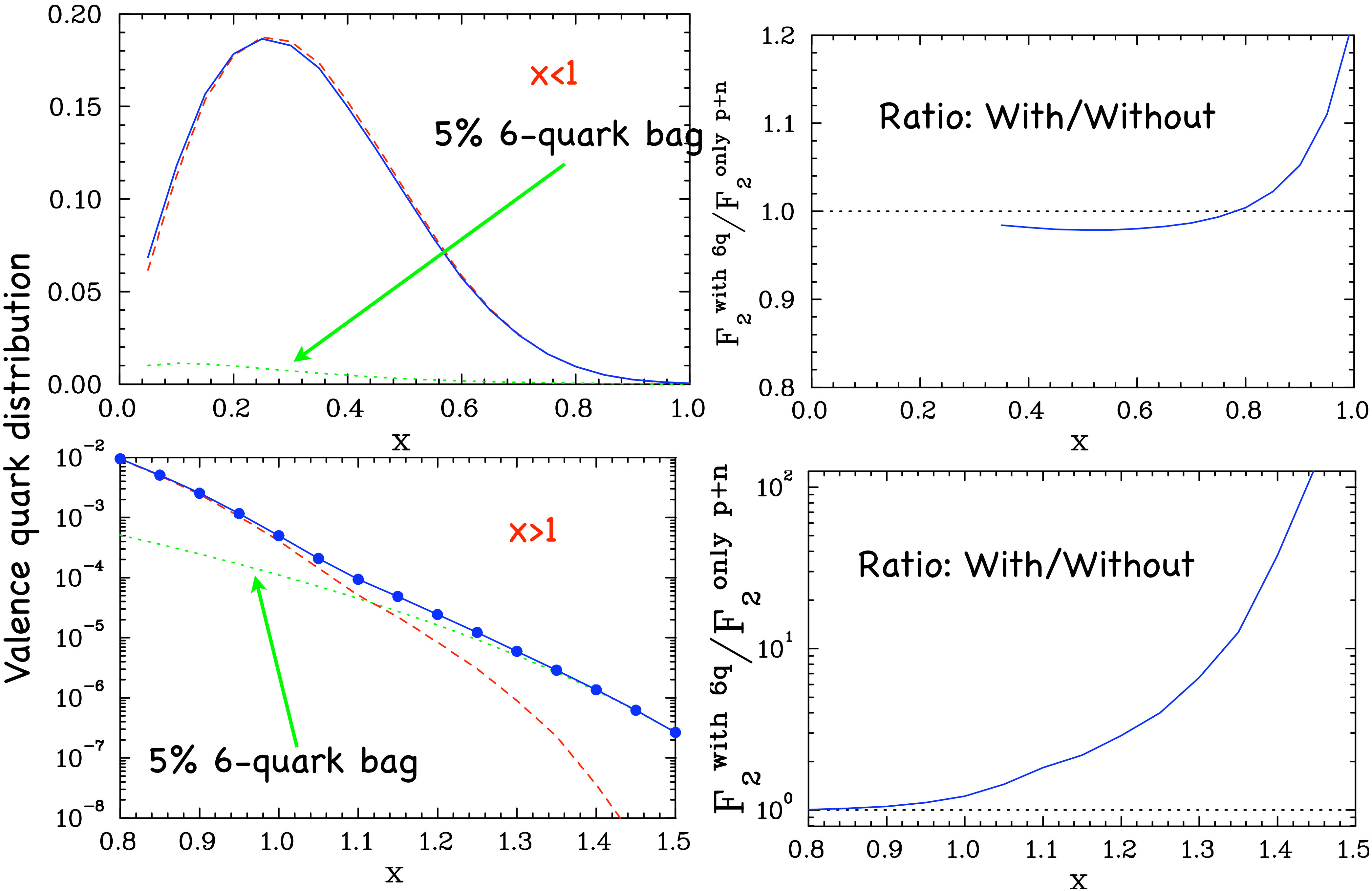
Even for a 1 fm separation, the central density is about 4x nuclear matter

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

Future Experiments

- 6 GeV
  - E-08-014: Three-nucleon short range correlations studies in inclusive scattering for $0.8 < 2.8$ $(GeV/c)^2$ [Hall A]
- 12 GeV
  - E12-06-105: Inclusive Scattering from Nuclei at $x > 1$ in the quasielastic and deeply inelastic regimes [Hall C]

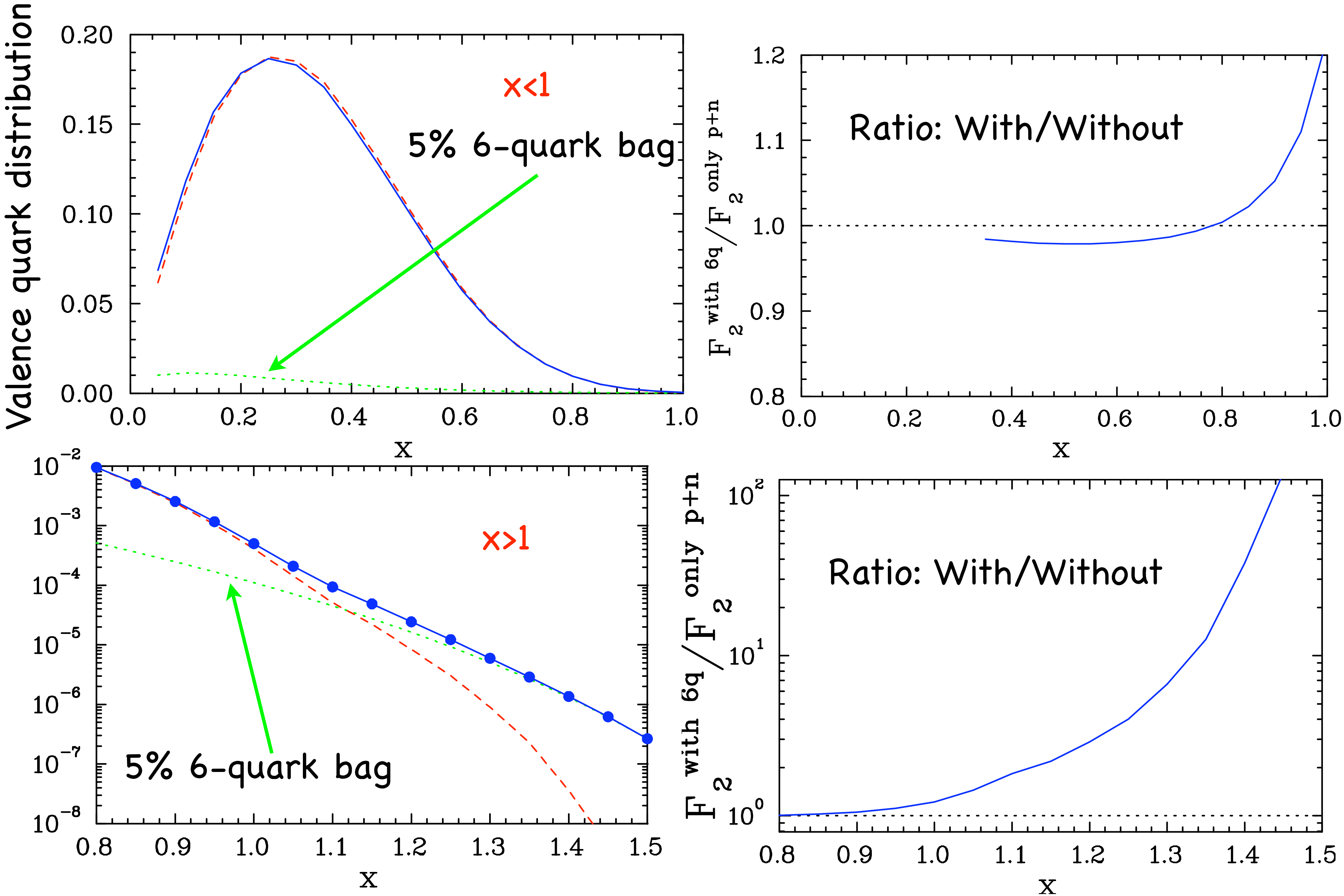
Motivation for E08-014

- Study onset of scaling, ratios as a function of α_{2n} for $1<x<2$
- Verify and define scaling regime for 3N-SRC
- 3N-SRC over a range of density: ^{40}Ca, ^{12}C, ^{4}He ratios
- Test α_{3n} for $x> 2$
- Absolute cross sections: test FSI, map out IMF distribution $\rho_A()$
  - needed for $q_A(x)$ convolution
  - (EMC, hard processes in A-A collisions, …)
- Isospin effects on SRCs: ^{48}Ca vs. ^{40}Ca

Finish

- Inclusive (e,e′) at large Q^2 scattering and x>1 is a powerful tool to explore long sought aspects of the NN interaction
  - Considerable body of data exists
- Provides access to SRC and high momentum components through scaling, ratios of heavy to light nuclei and allows systematic studies of FSI
- Scaling in ξ appears to work well even in regions where the DIS is not the dominate process
  - DIS is does not dominate over QES at 6 GeV but should at 11 GeV and at Q^2 > 10 - 15 $(GeV/c)^2$. We can expect that any scaling violations will vanish as we go to higher Q^2
- Once DIS dominates it will allow another avenue of access to SRC and to quark distribution functions
- We need theoretical guidance to understand the connections between the different scaling behaviors.

Sensitivity to non-hadronic components



Mulders & Thomas

Quark distributions at x > 1

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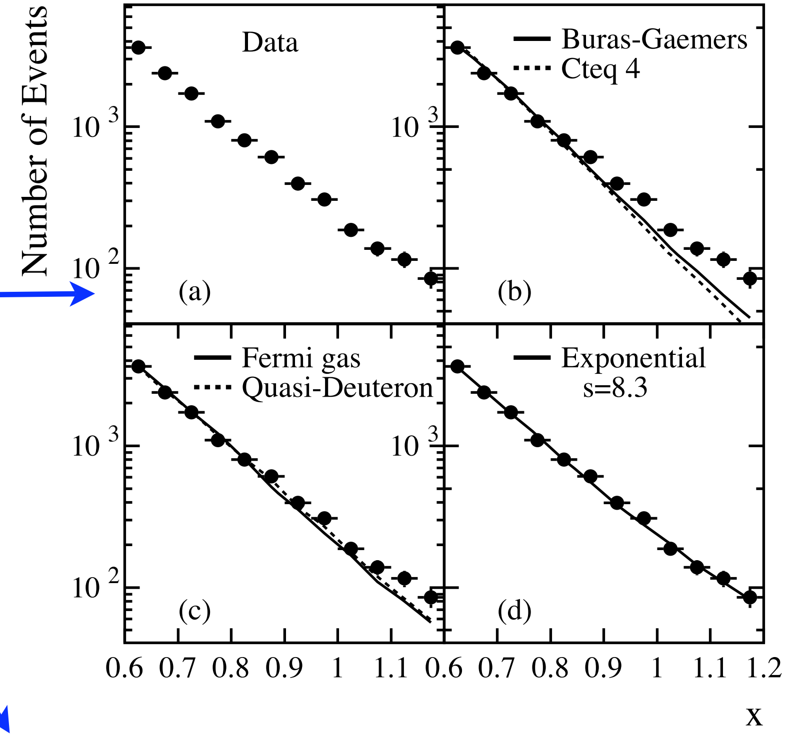
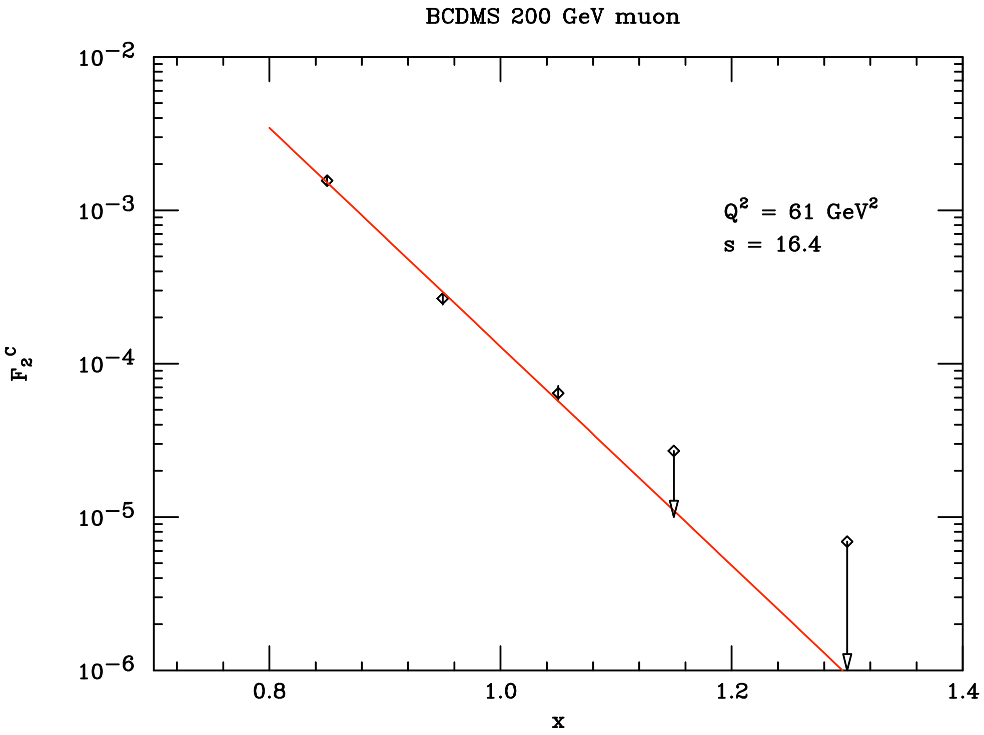
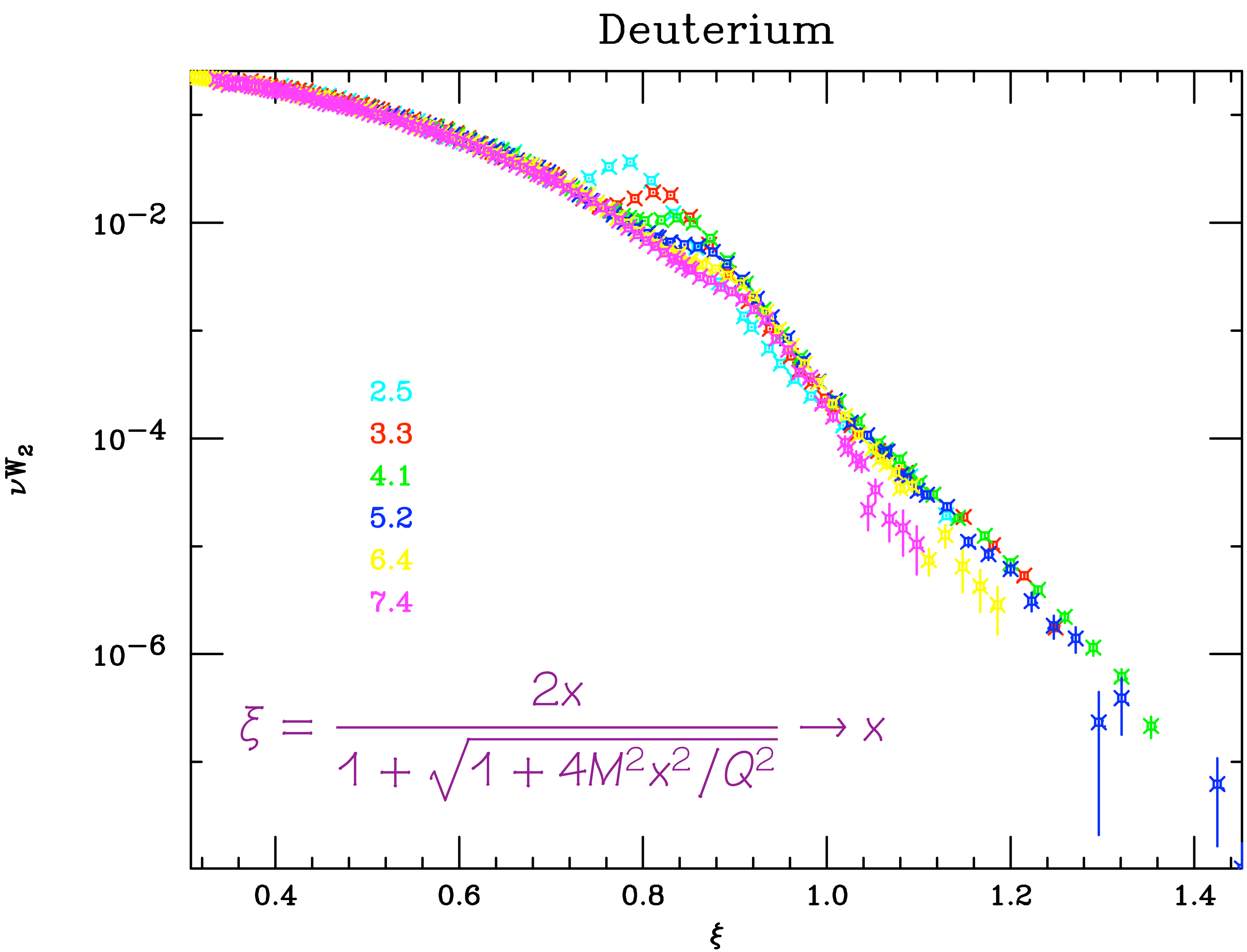




With 11 GeV beam, we should be in the scaling region up to x≈1.4

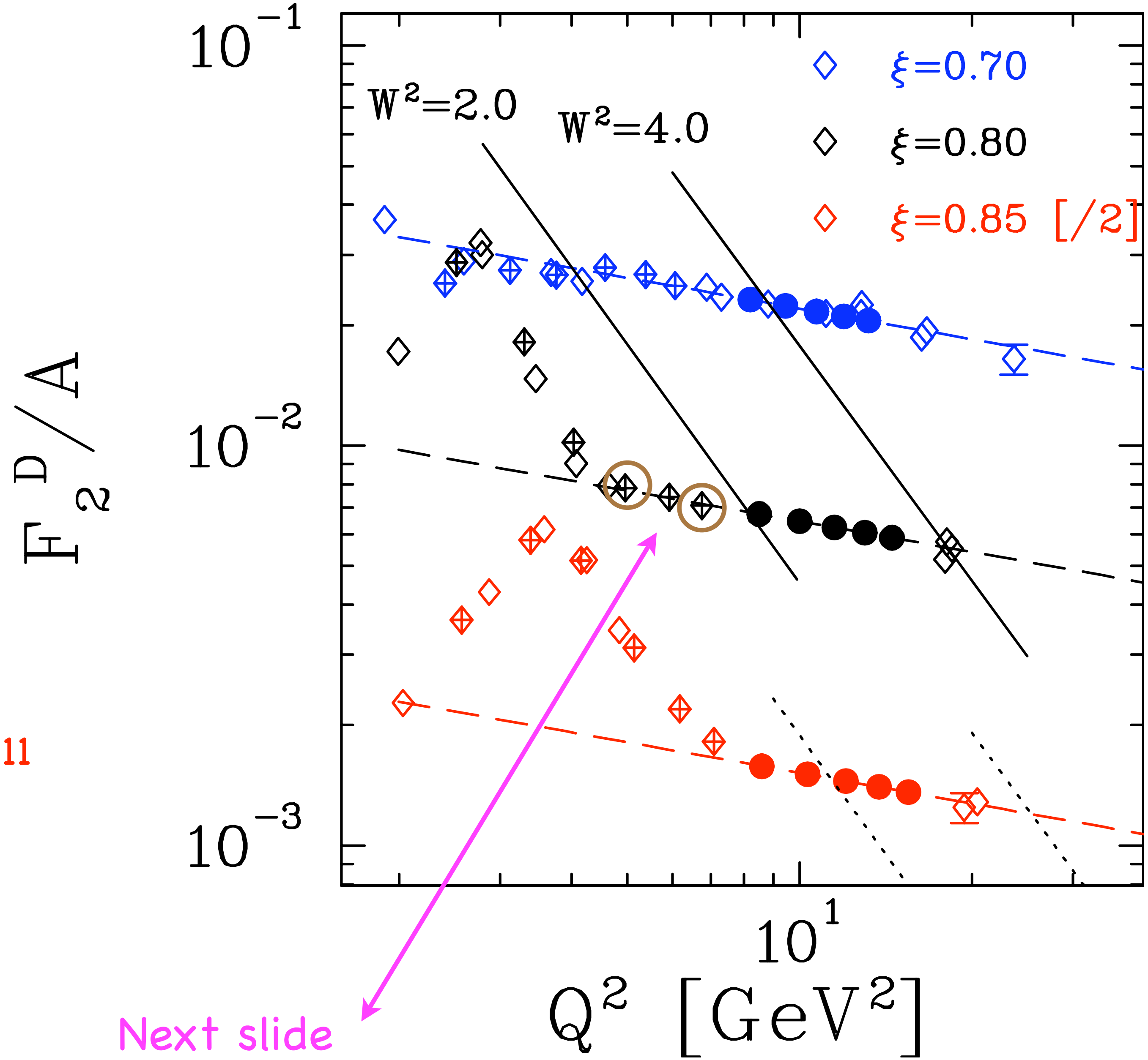
Quark Distribution Functions



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

DIS at x > 1 or studying Superfast Quarks

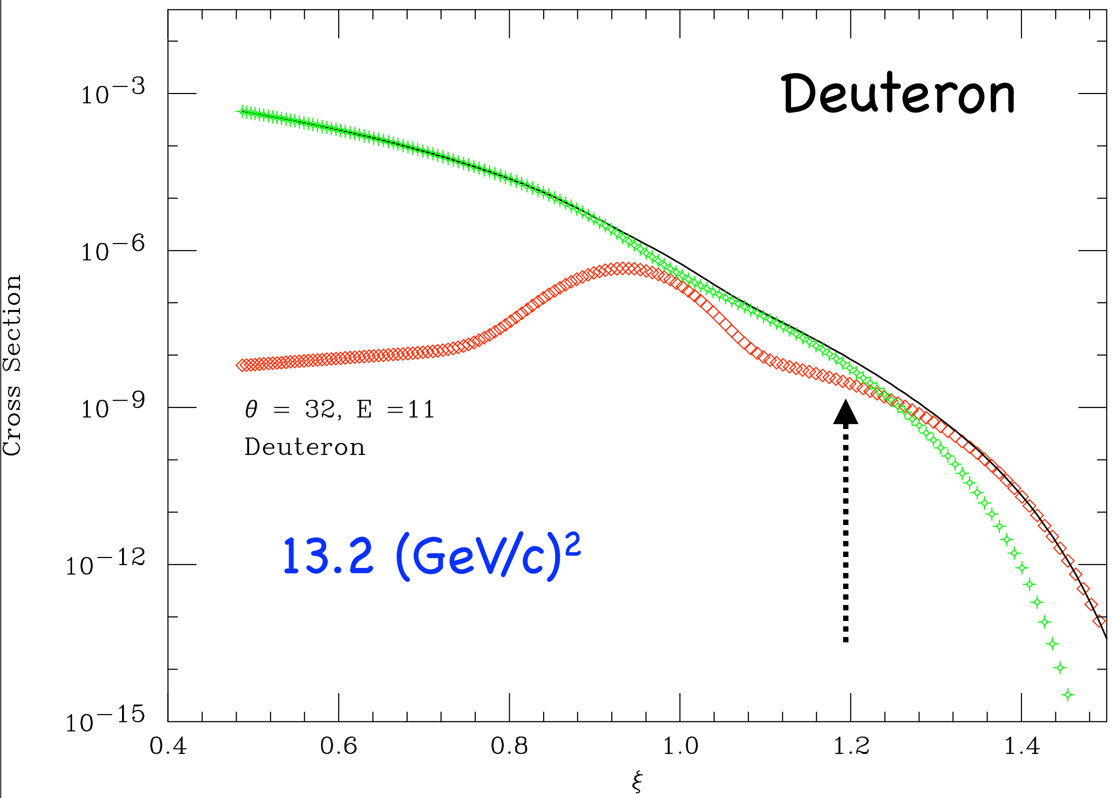
- In the nucleus we can have 0<x<A
- In the Bjorken limit, x > 1 DIS tells us the virtual photon scatters incoherently from quarks
- Quarks can obtain momenta x>1 by abandoning confines of the nucleon
  - deconfinement, color conductivity, parton recombination multiquark configurations
  - correlations 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

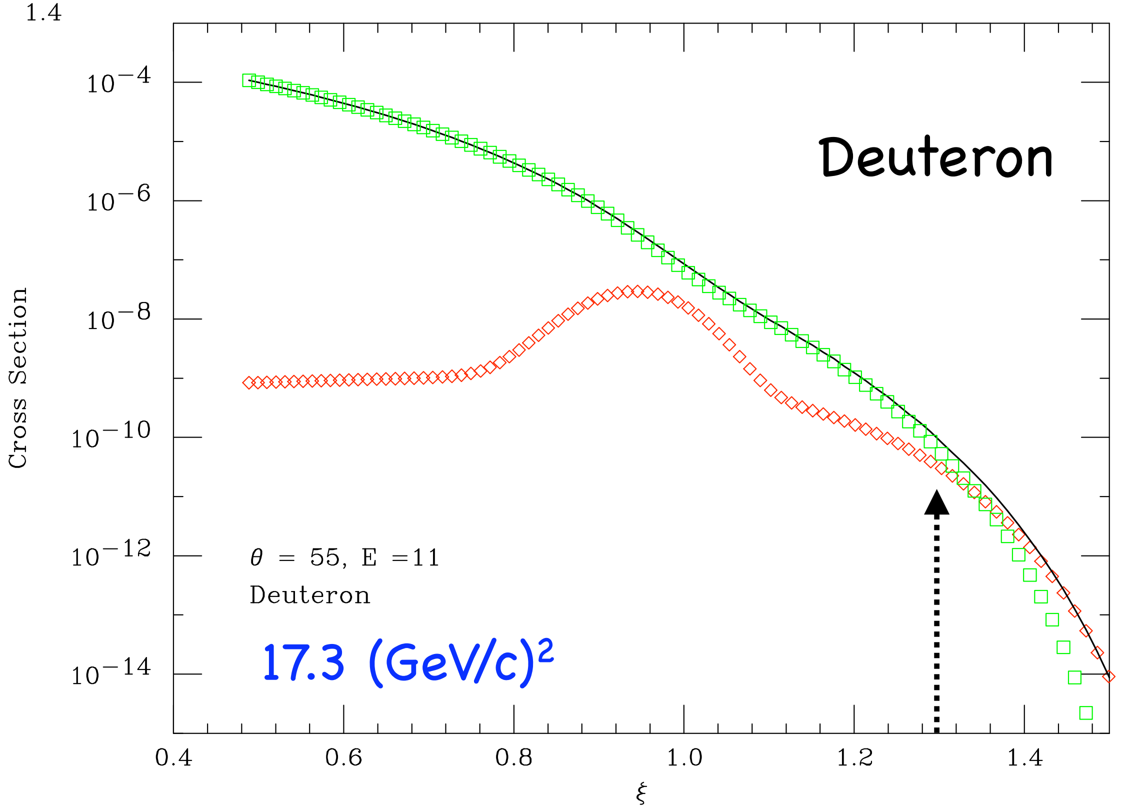
Predictions for 11 GeV



Convolution model

QES

DIS + RR



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

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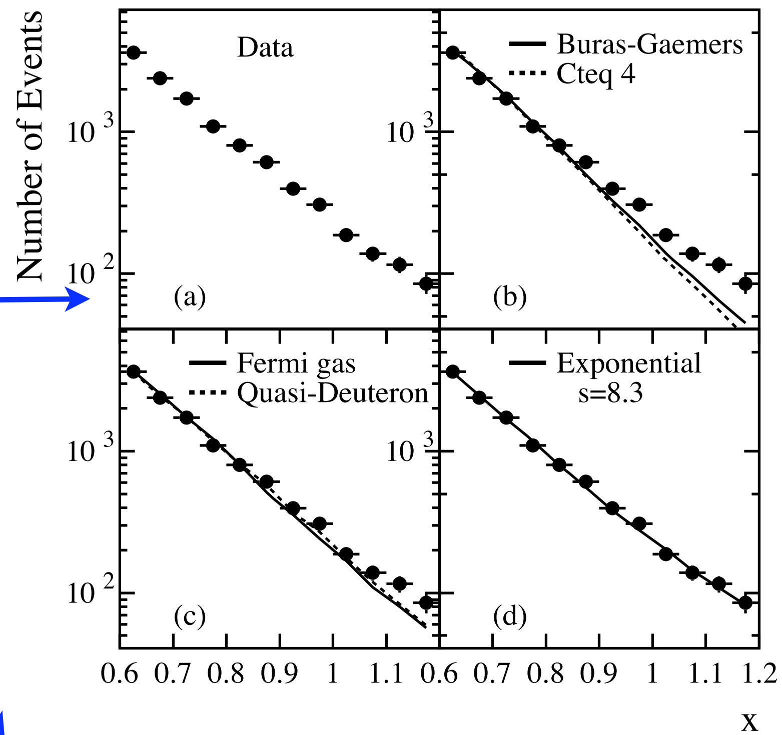
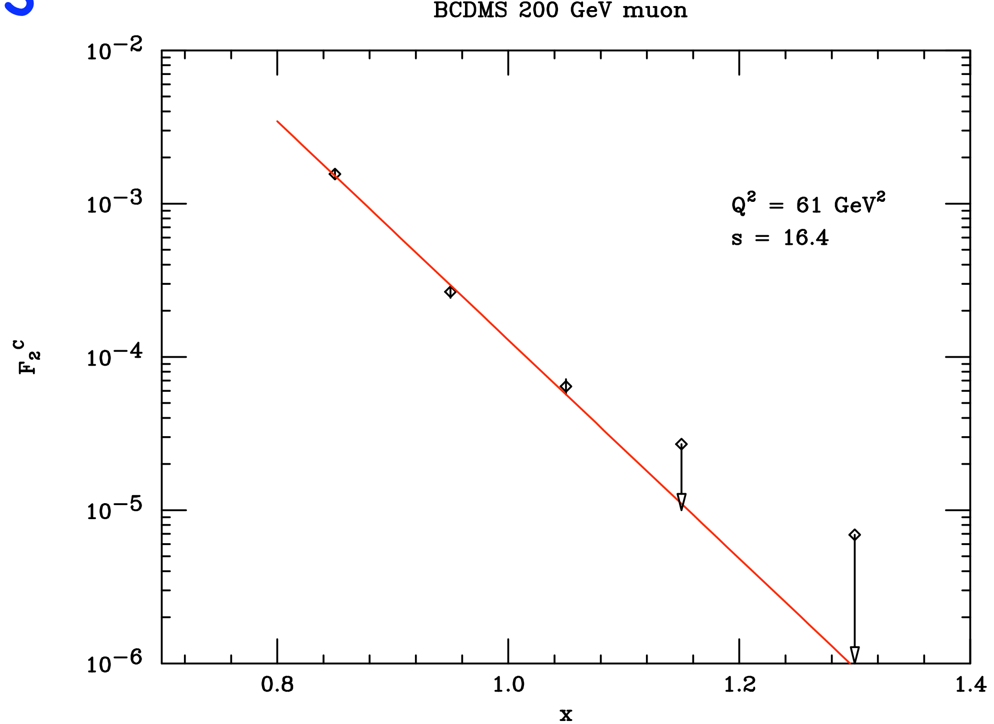


Jlab data fitted to e^{-sx} gives back s = 16.



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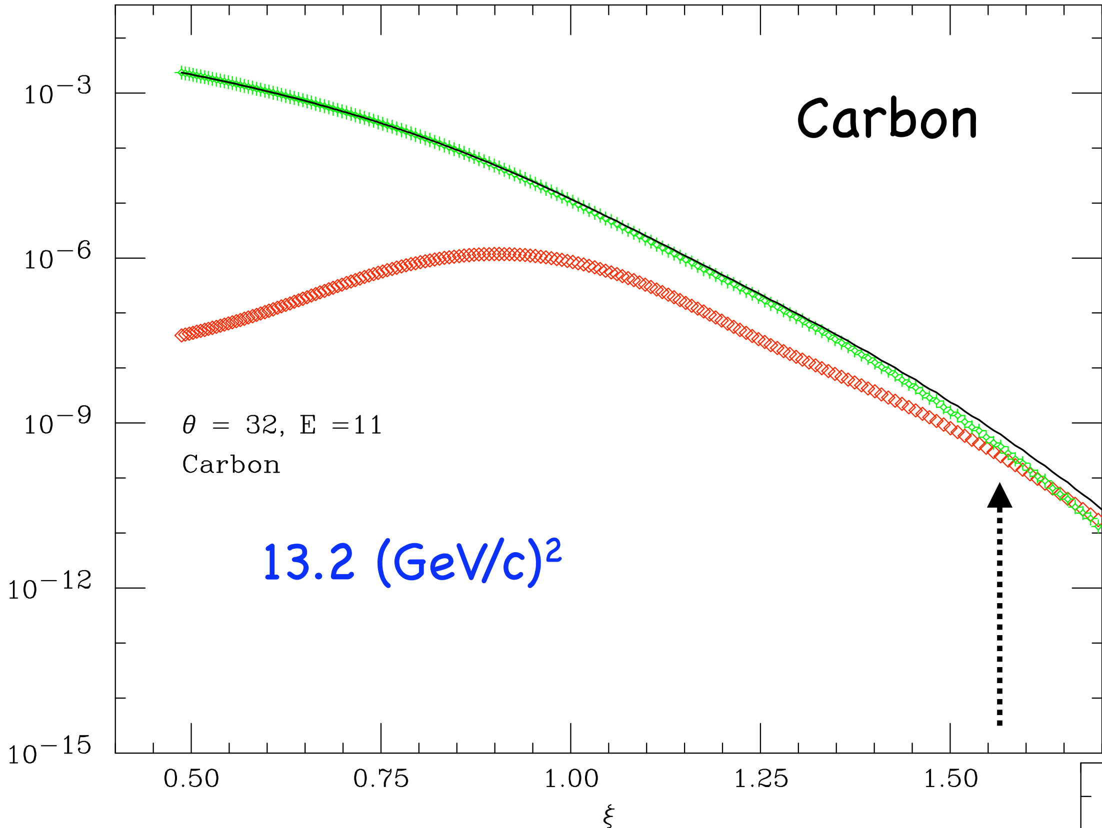

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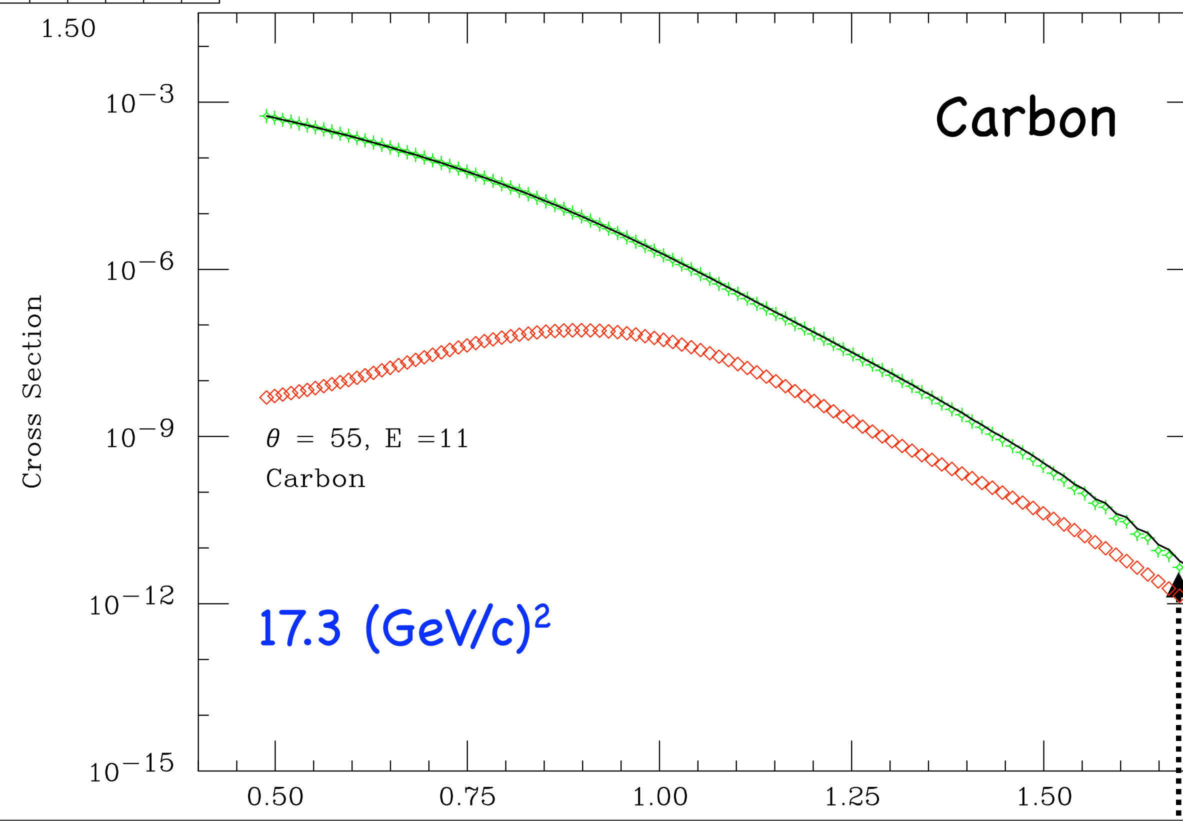

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