SRC and x > 1 at 12 GeV
What can we learn?

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Short Range Correlations in Nuclei and Hard QCD Phenomena

ECT* Trento, November 14 - 18 2011

Prologue

Inclusive electron scattering has not fallen out of fashion even in the presence of cw accelerators).

Why?

Because it still provides a rich, albeit 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 $x > 1$

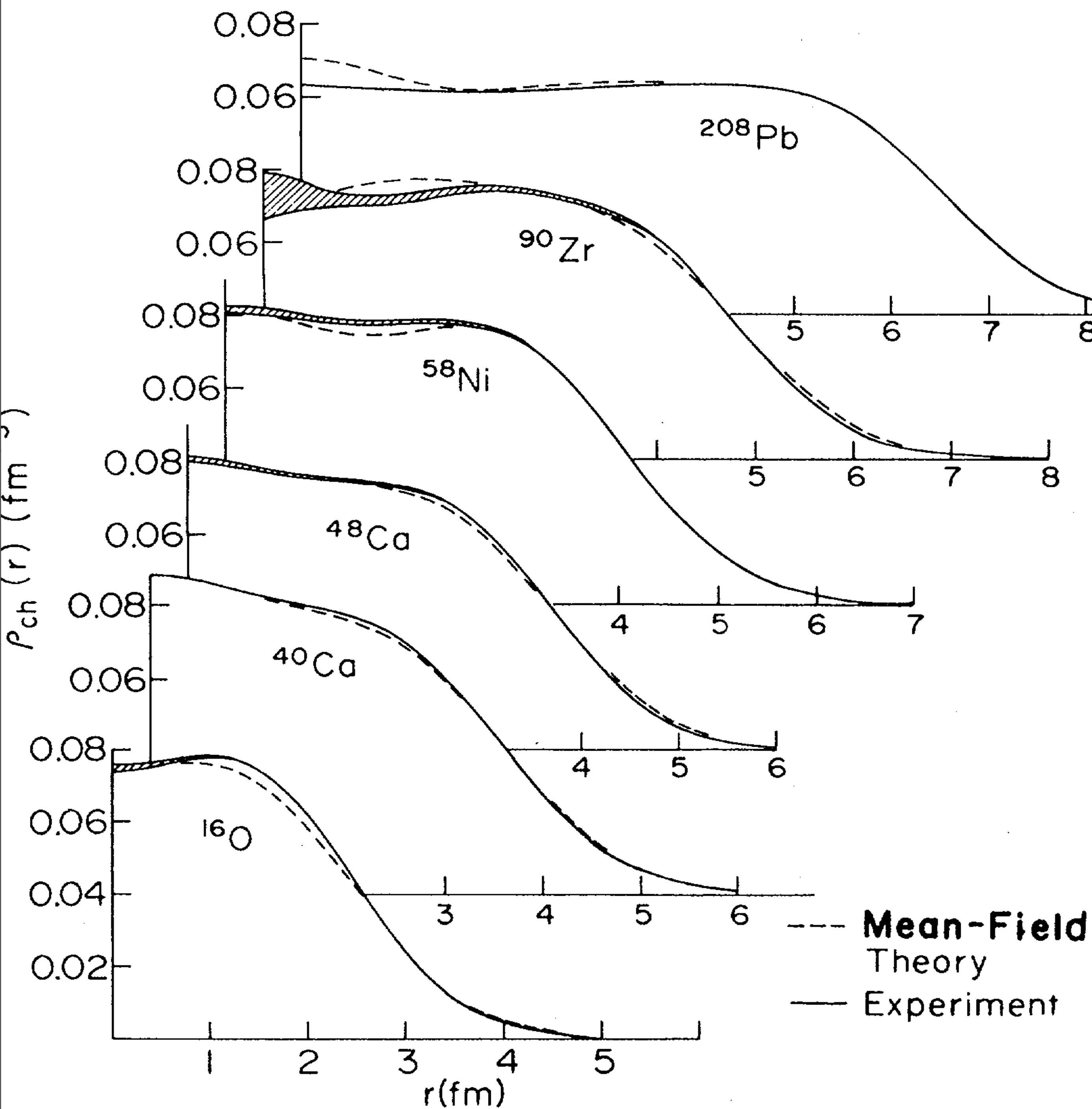
The inclusive nature of these studies make disentangling all the different pieces a challenge but experiments over a range of Q^2 and with different A will help.

Interpretation demands theoretical input

Outline

- Short range Correlations
- Inelastic Electron Scattering
- Do FSI obstruct us from gleaning information about SRCs in inclusive electron scattering?
- Ratios and FSI
- Transition from the study of correlations in QES to correlations in DIS
- New experiments

How do we know short range correlations exist?



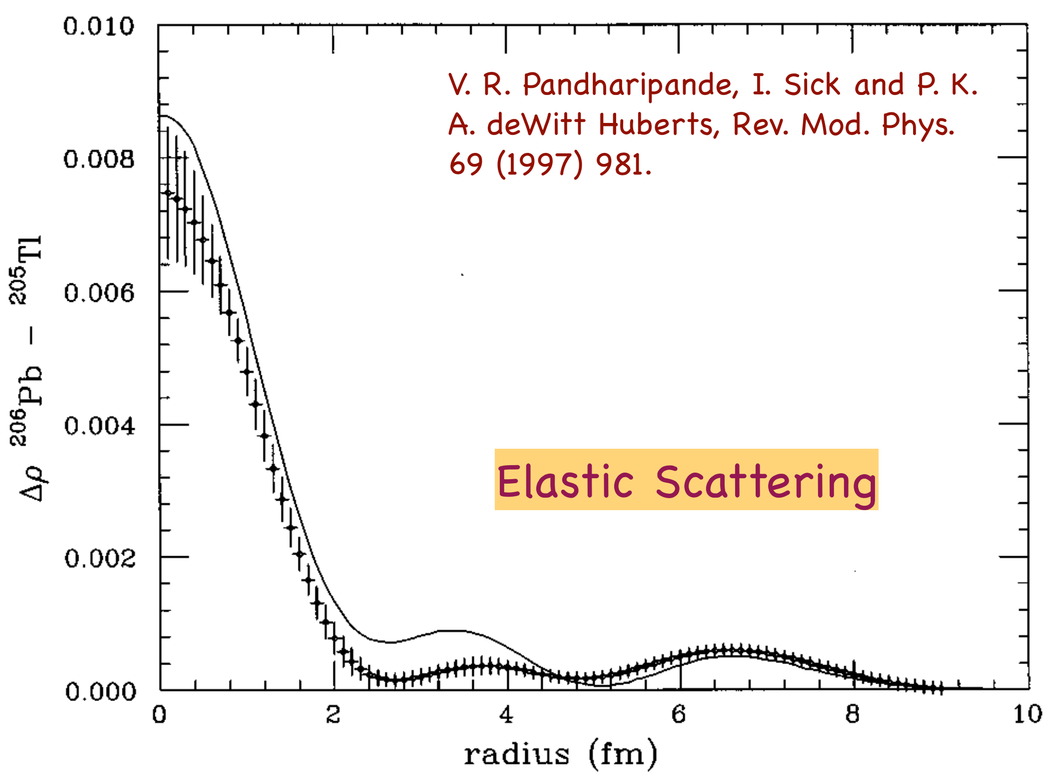
Central density is saturated - nucleons can be packed only so close together: ρ_{ch} * (A/Z) = constant

Spatial correlations

J.W. Negele RMP 54 (913) 1982

O. Benhar, AIP Conf.Proc. 1189 (2009) 43-50

What else - Occupation Numbers?

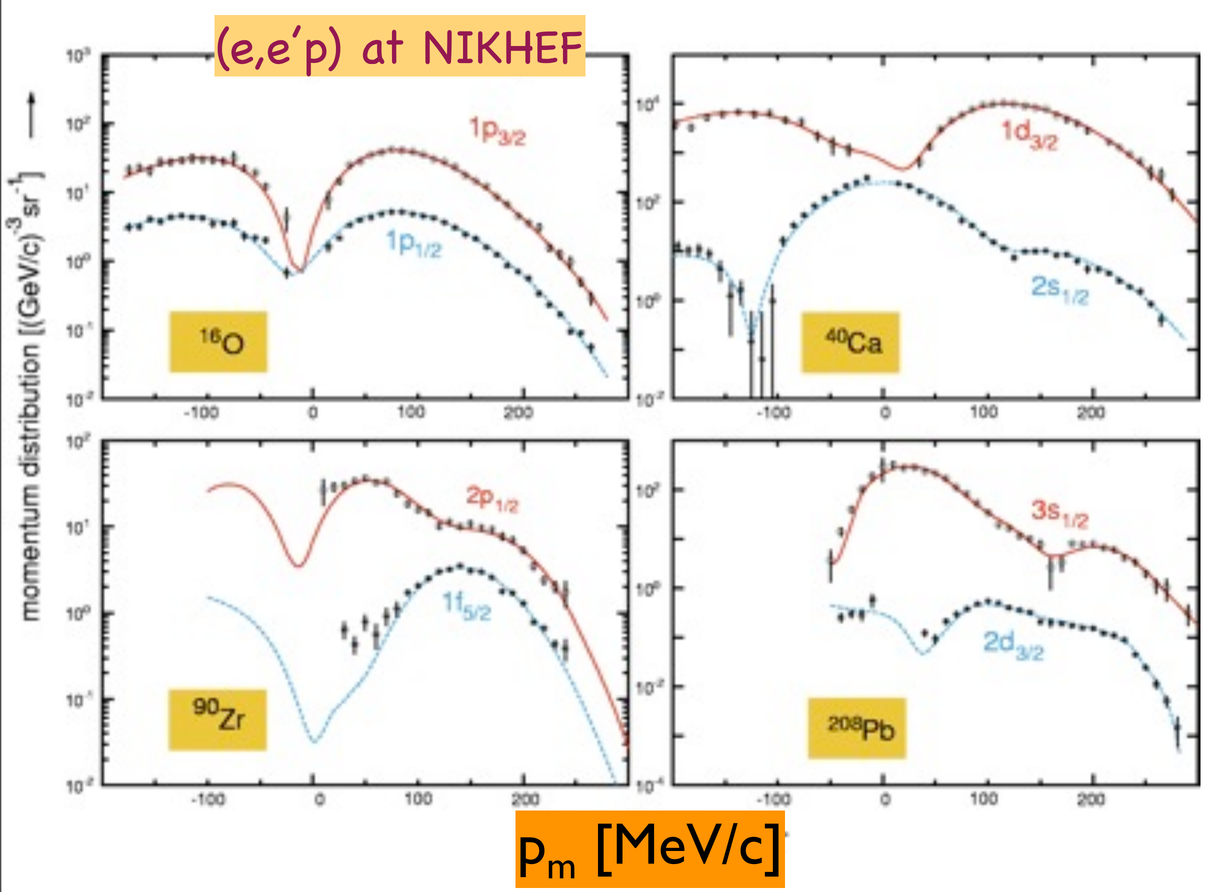


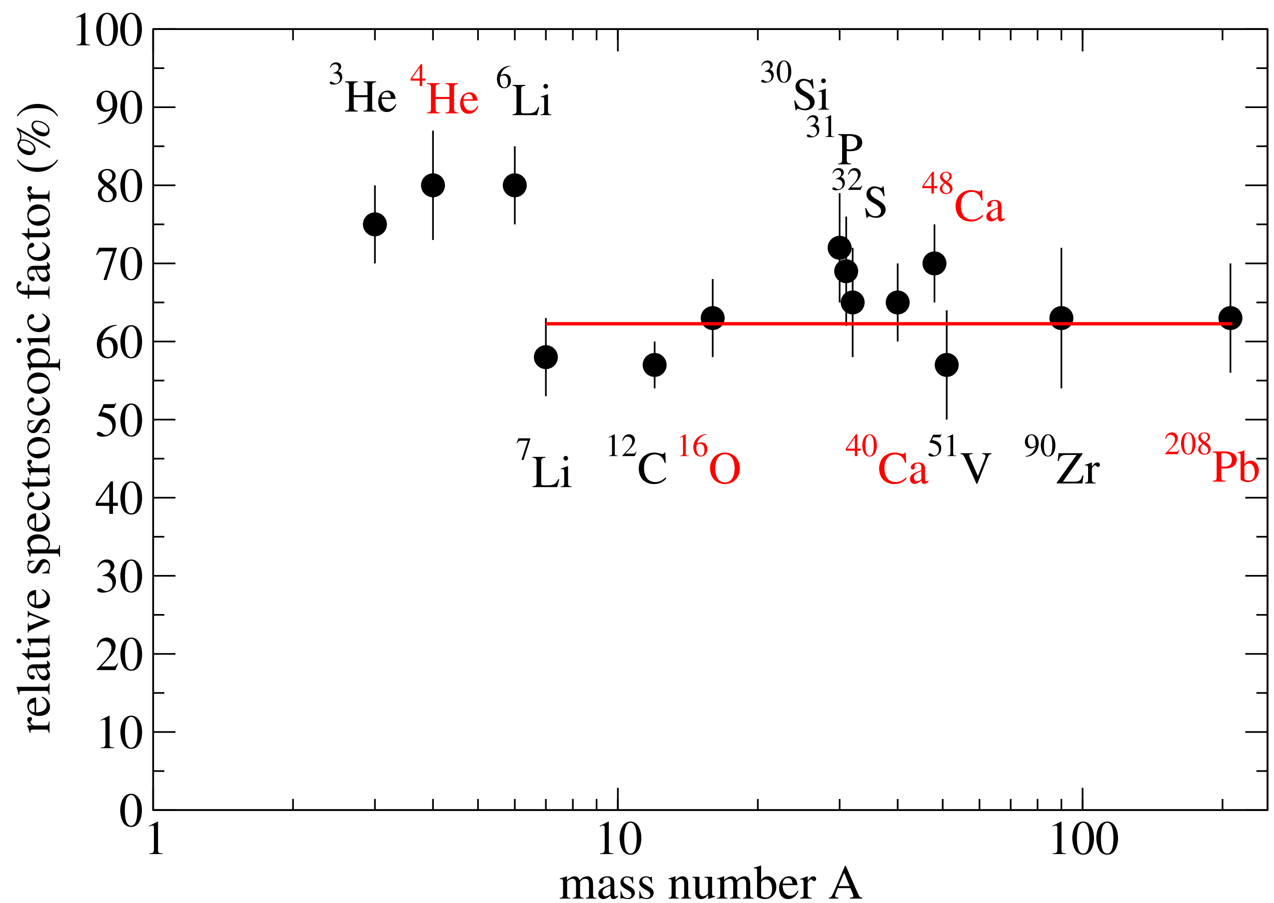
Density difference between ^{206}Pb and ^{205}Tl.

Experiment - Cavedon et al (1982)
Theory: Hartree-Fock orbitals with adjusted occupation numbers is given by the curve.

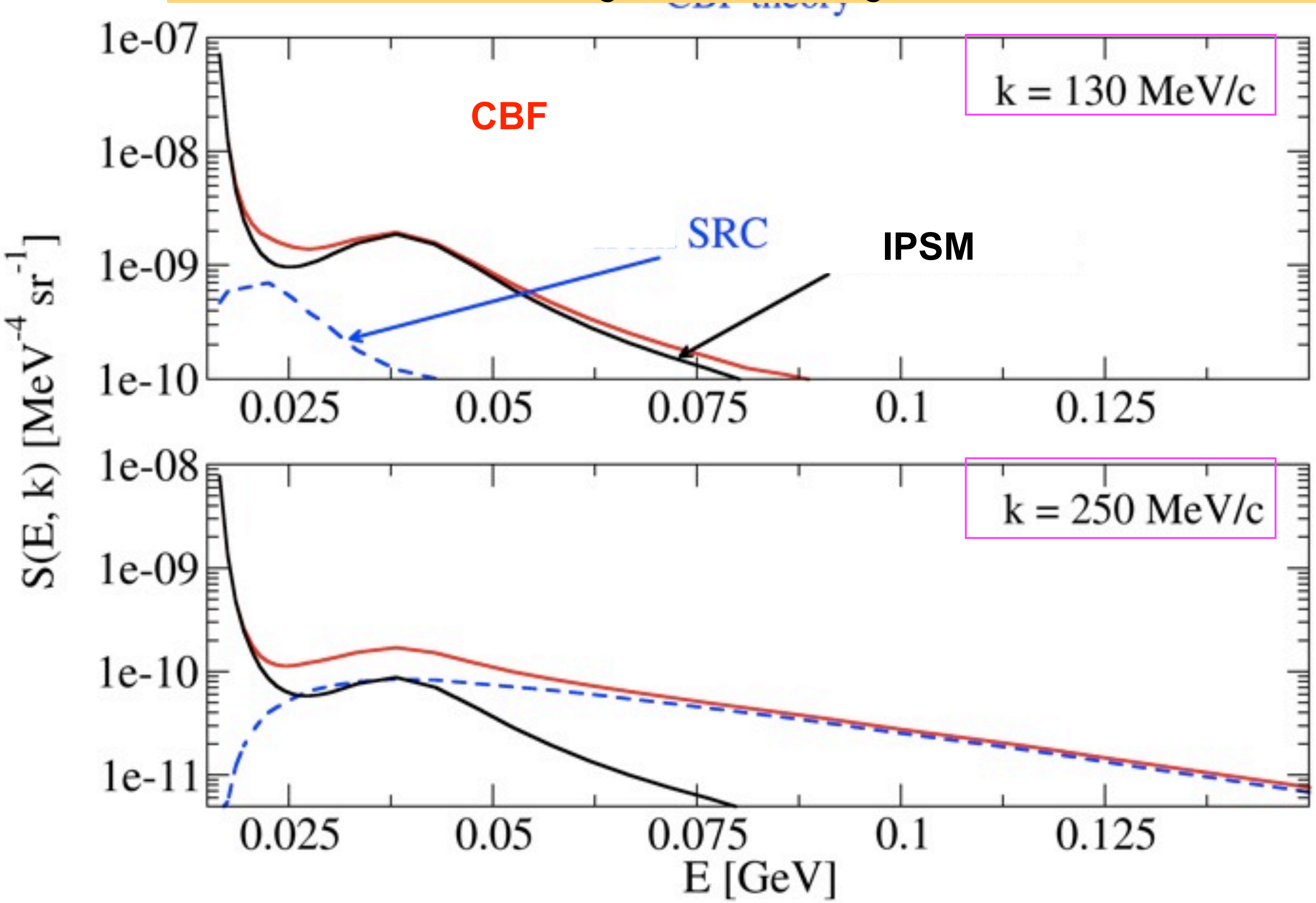
The shape of the $3s^{1/2}$ orbit is very well given by the mean field calculation.

Occupation numbers scaled down by a factor ~0.65.





Realistic many body calculations of the spectral function contain correlated strength and it is significant



Benhar via Rohe ^{12}C

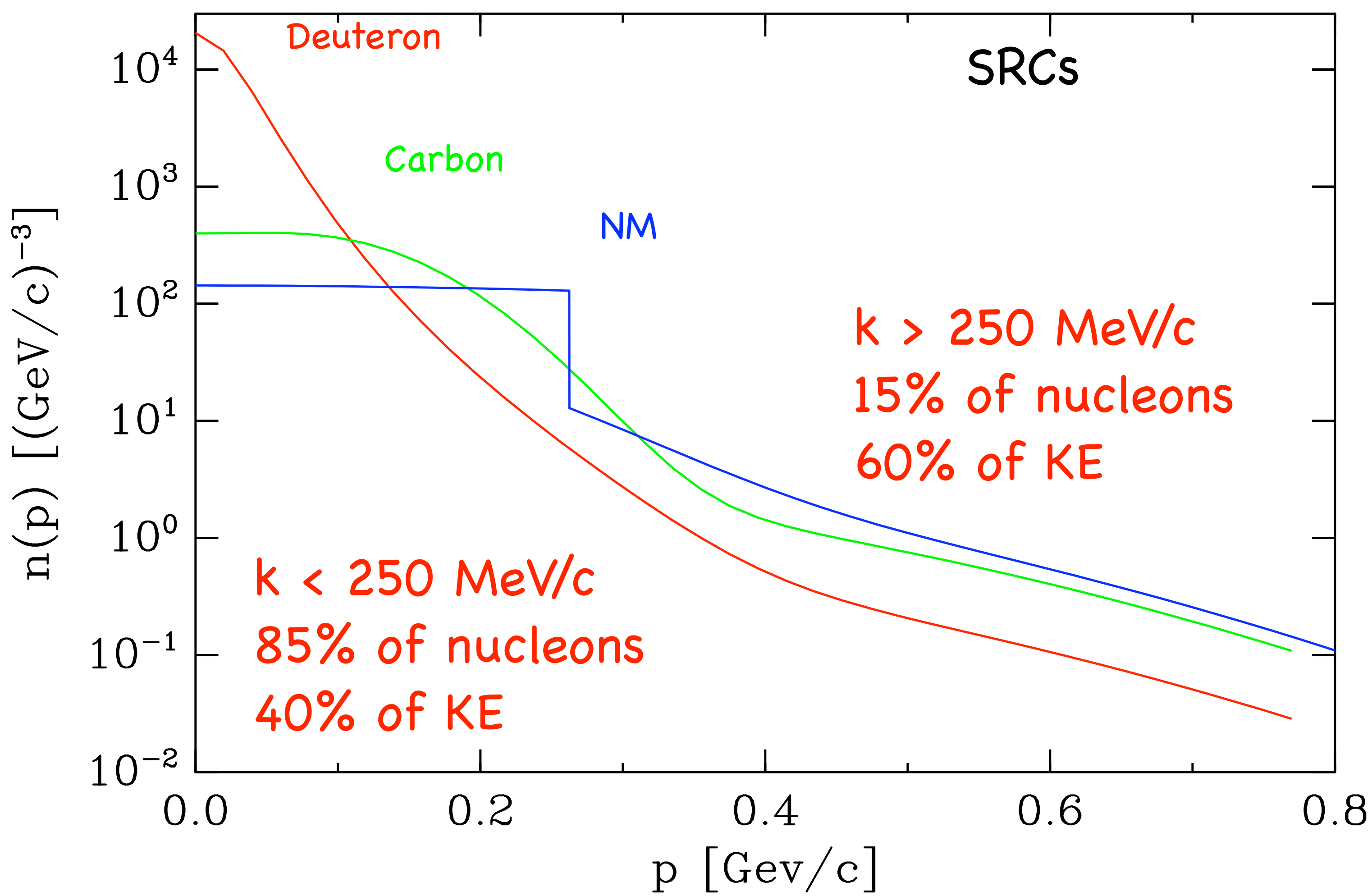
$\approx k_F$

$k < k_F$: single-particle contribution dominates

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

$k > k_F$: single-particle negligible

What many calculations indicate is that the tail of n(k) for different nuclei has a similar shape - reflecting that it is the short distance part of the NN interactions, common to all nuclei, is the source of these dynamical correlations.

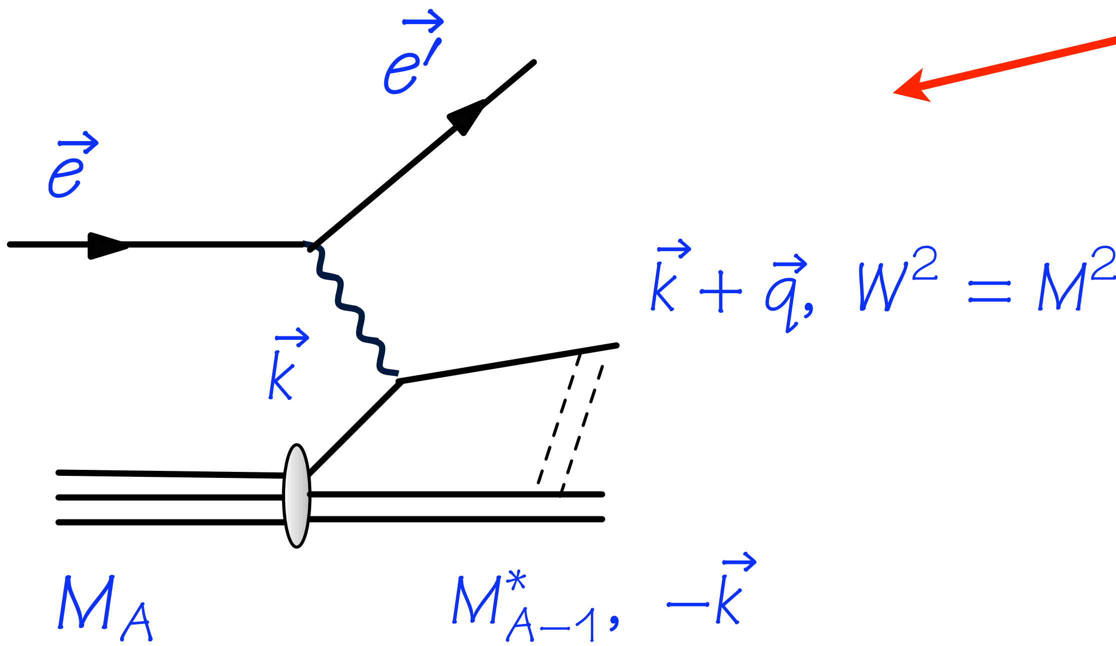


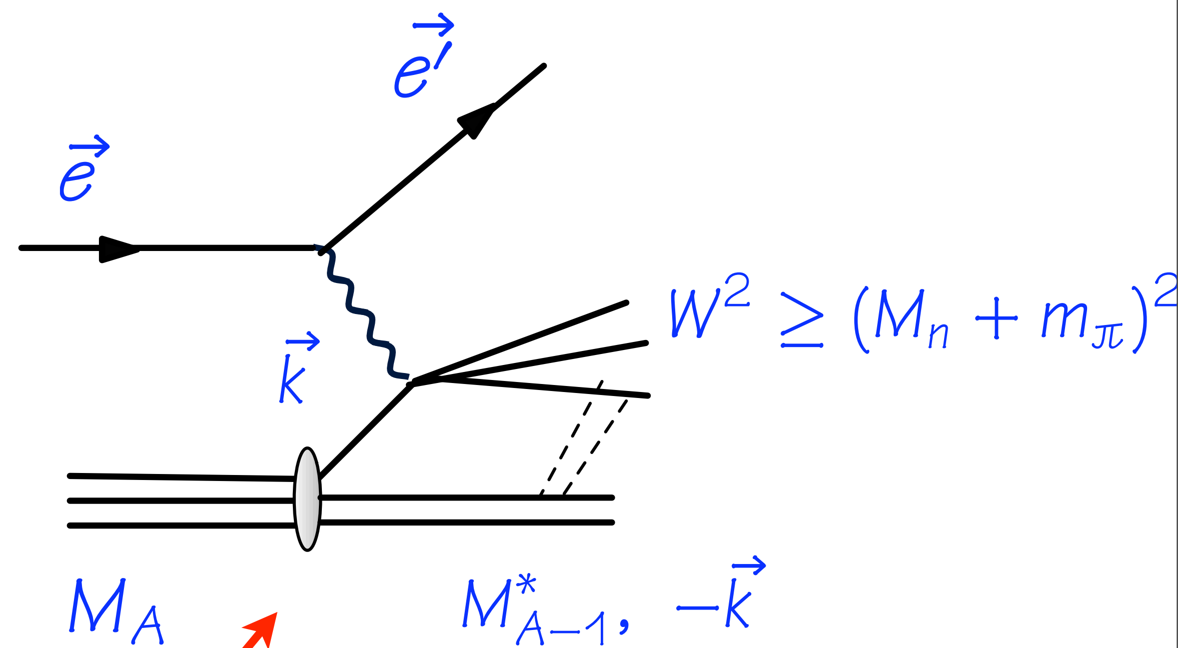
Search for SRC in inclusive (e,e') experiments

Inclusive Electron Scattering from Nuclei

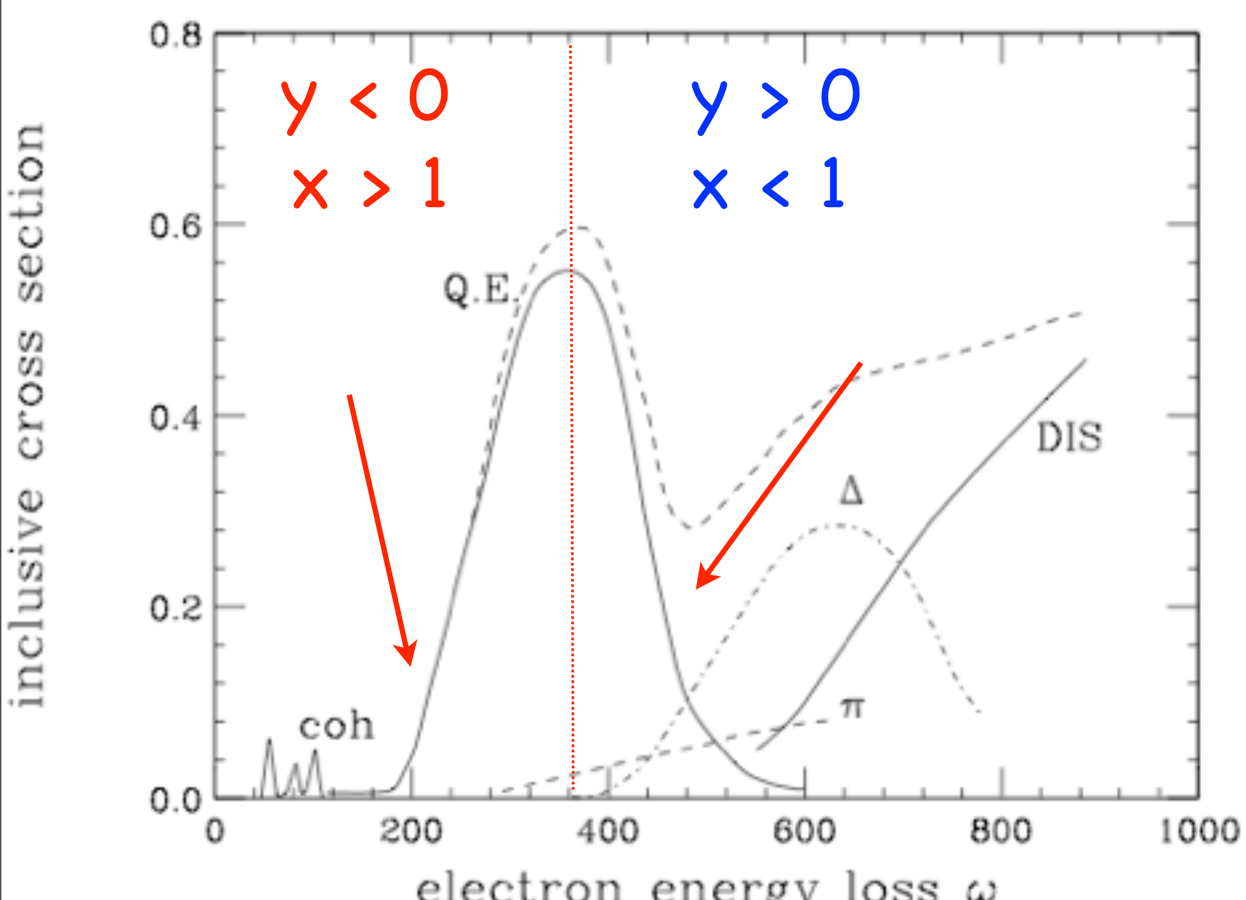
Two dominant and distinct processes

Quasielastic from the nucleons in the nucleus





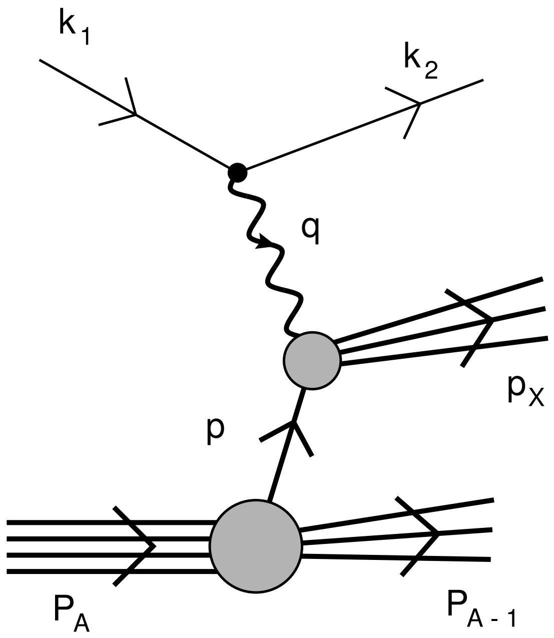
Inelastic (resonances) and DIS from the quark constituents of the nucleon.



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

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

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

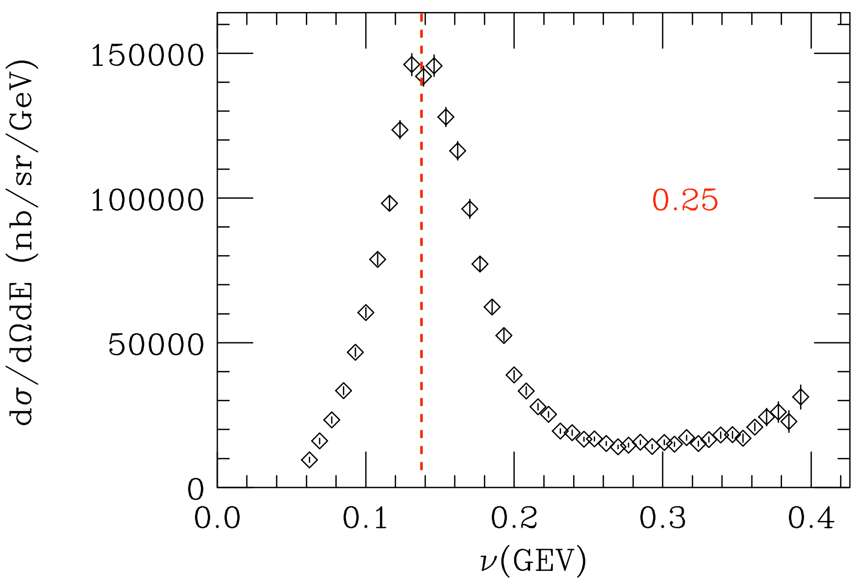
However they have very different Q^2 dependencies

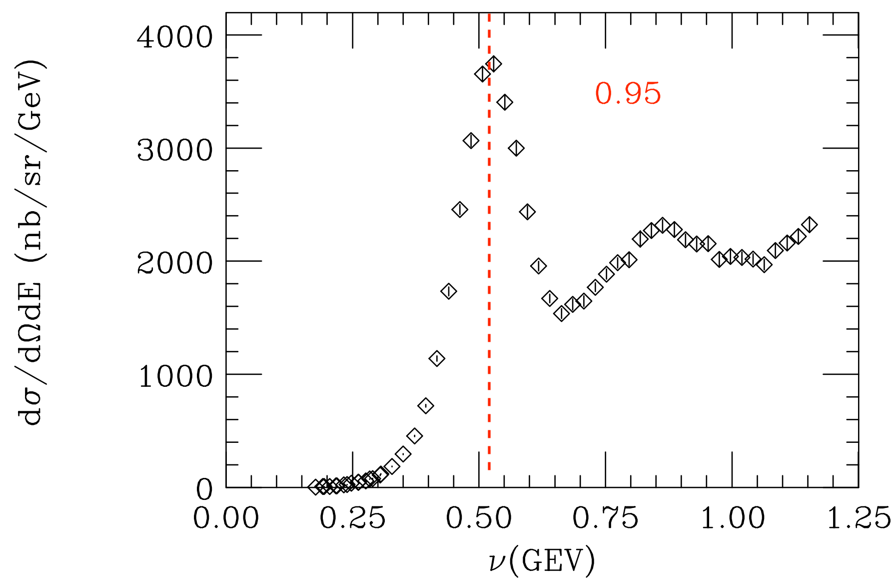
$\sigma_{ei} \propto$ elastic (form factor)^2 $\approx 1/Q^4$

$W_{1,2}$ scale with ln Q^2 dependence

Exploit this dissimilar Q^2 dependence

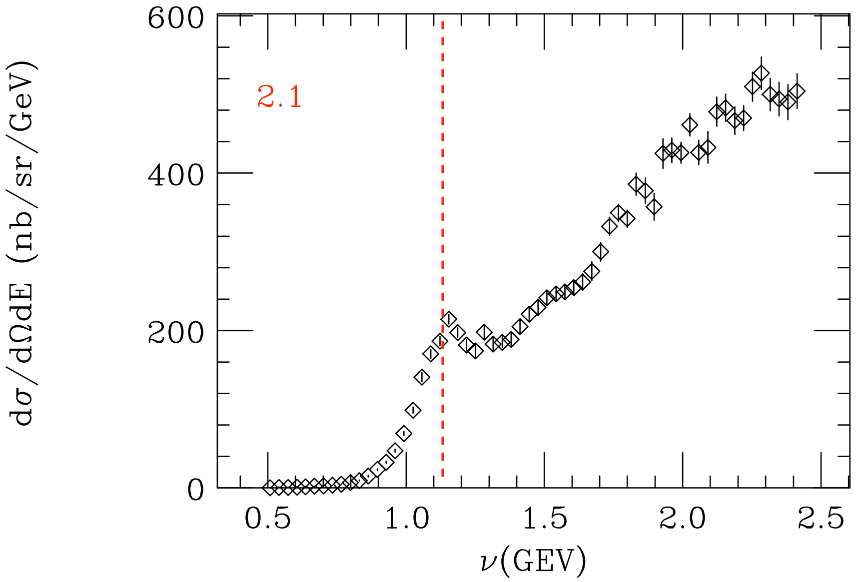
Shape of QES Spectrum

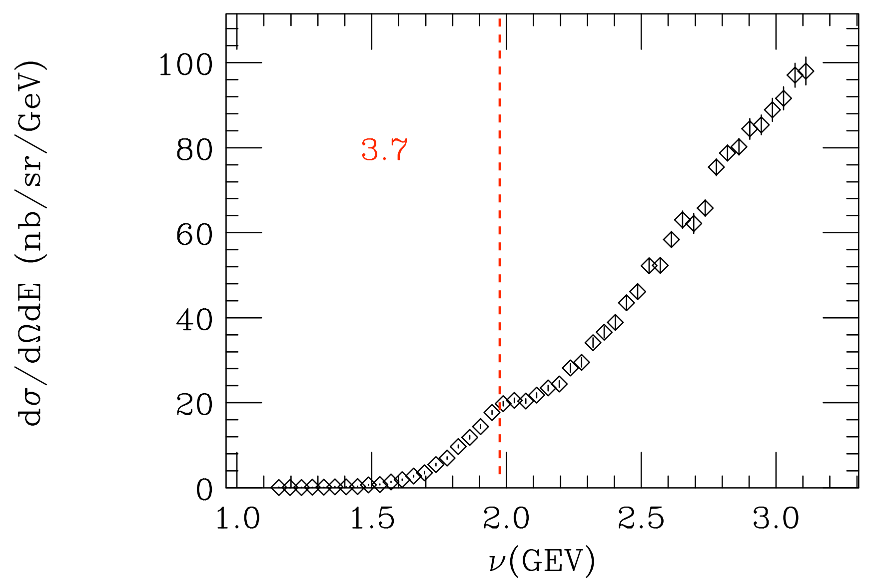




8°, E from 3- 15 GeV

^{3}He SLAC (1979)



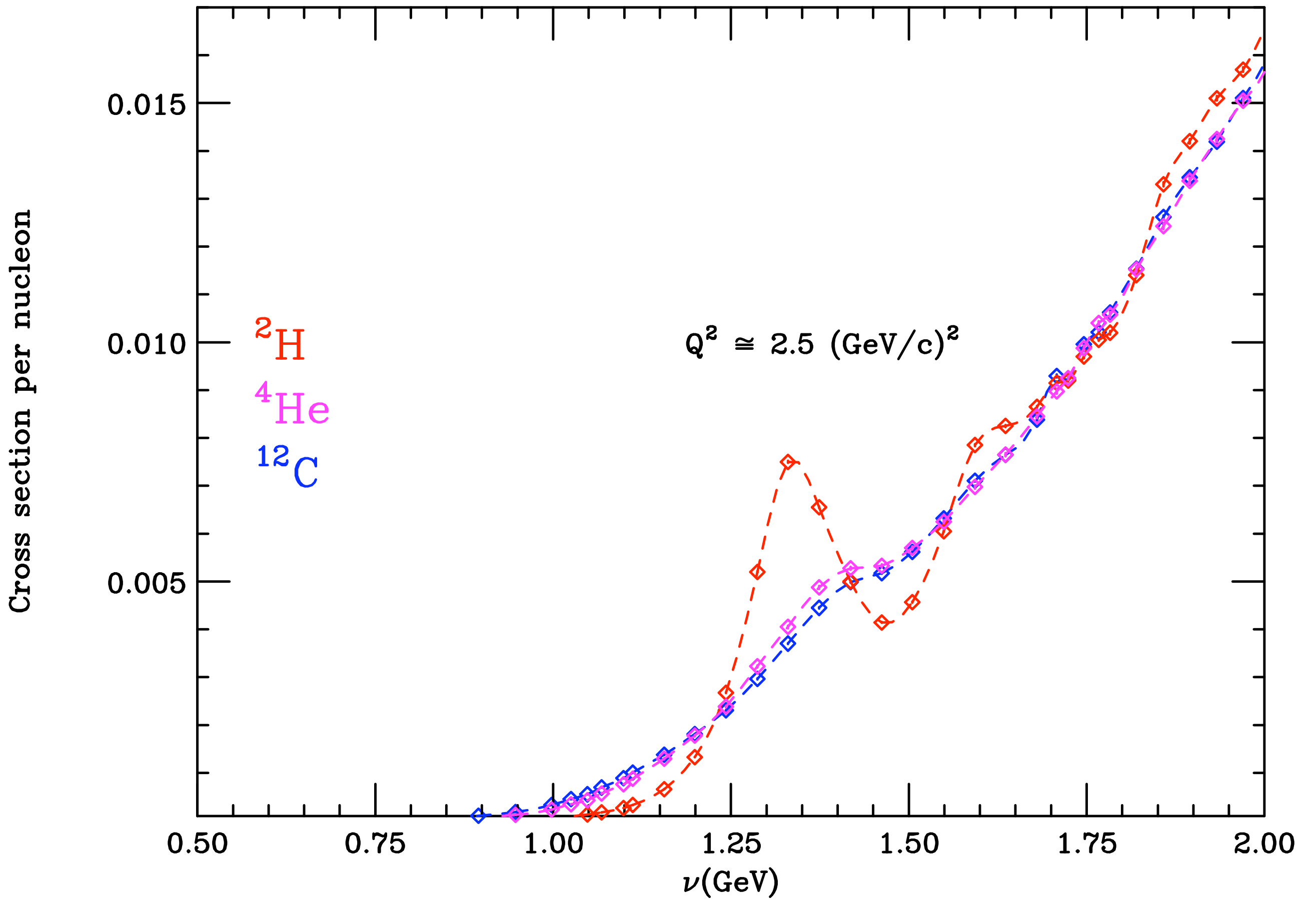


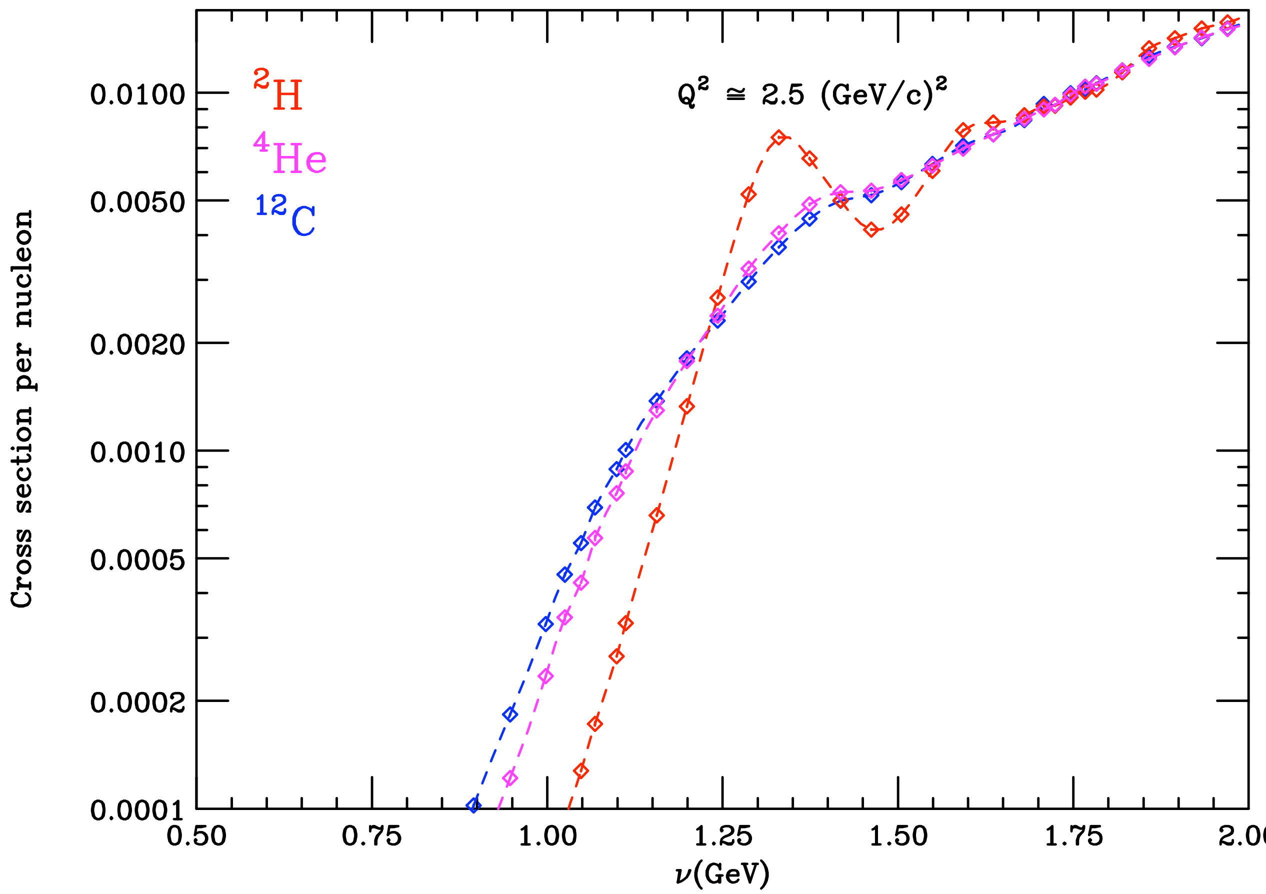
The quasielastic peak (QE) is broadened by the Fermi-motion of the struck nucleon.

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

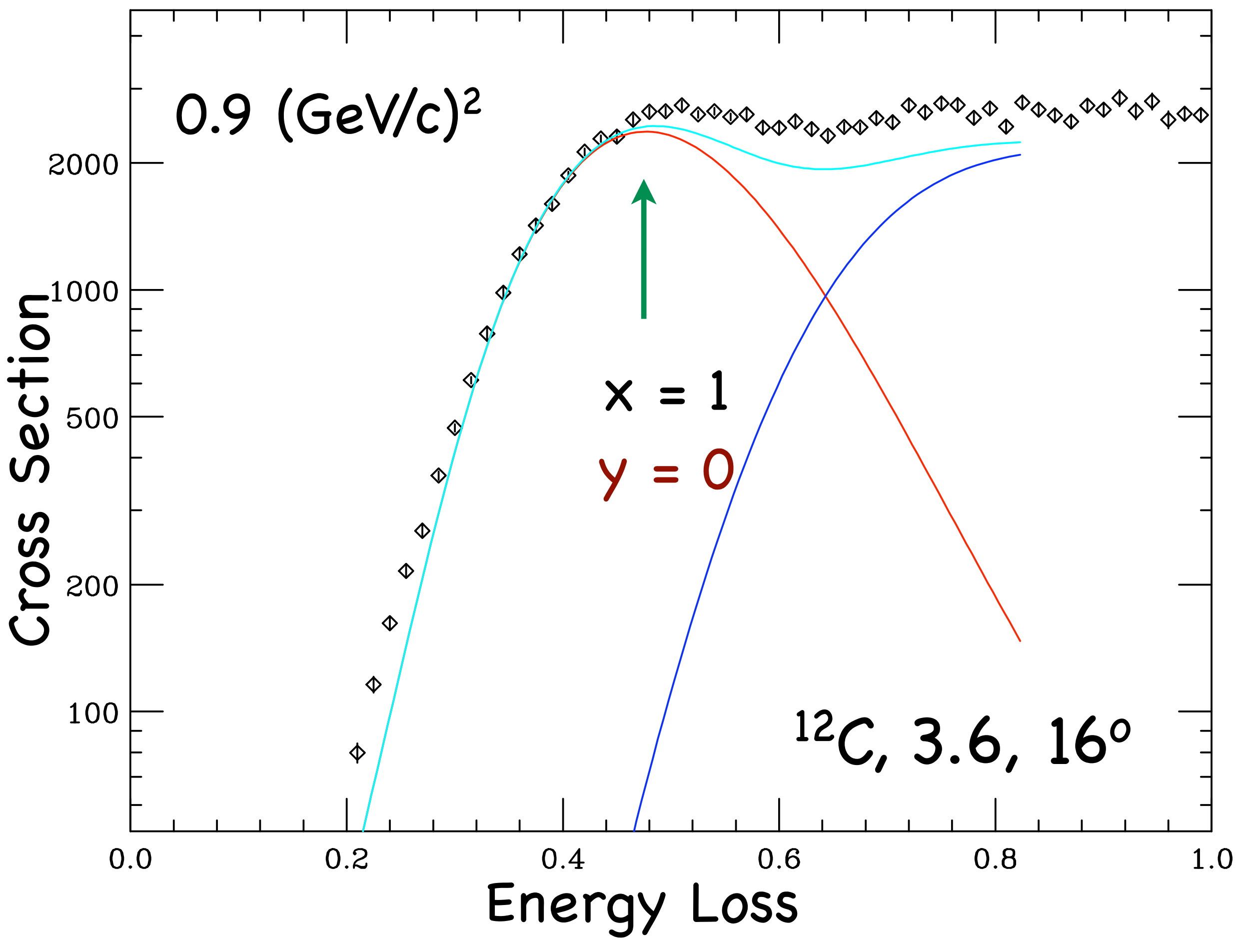


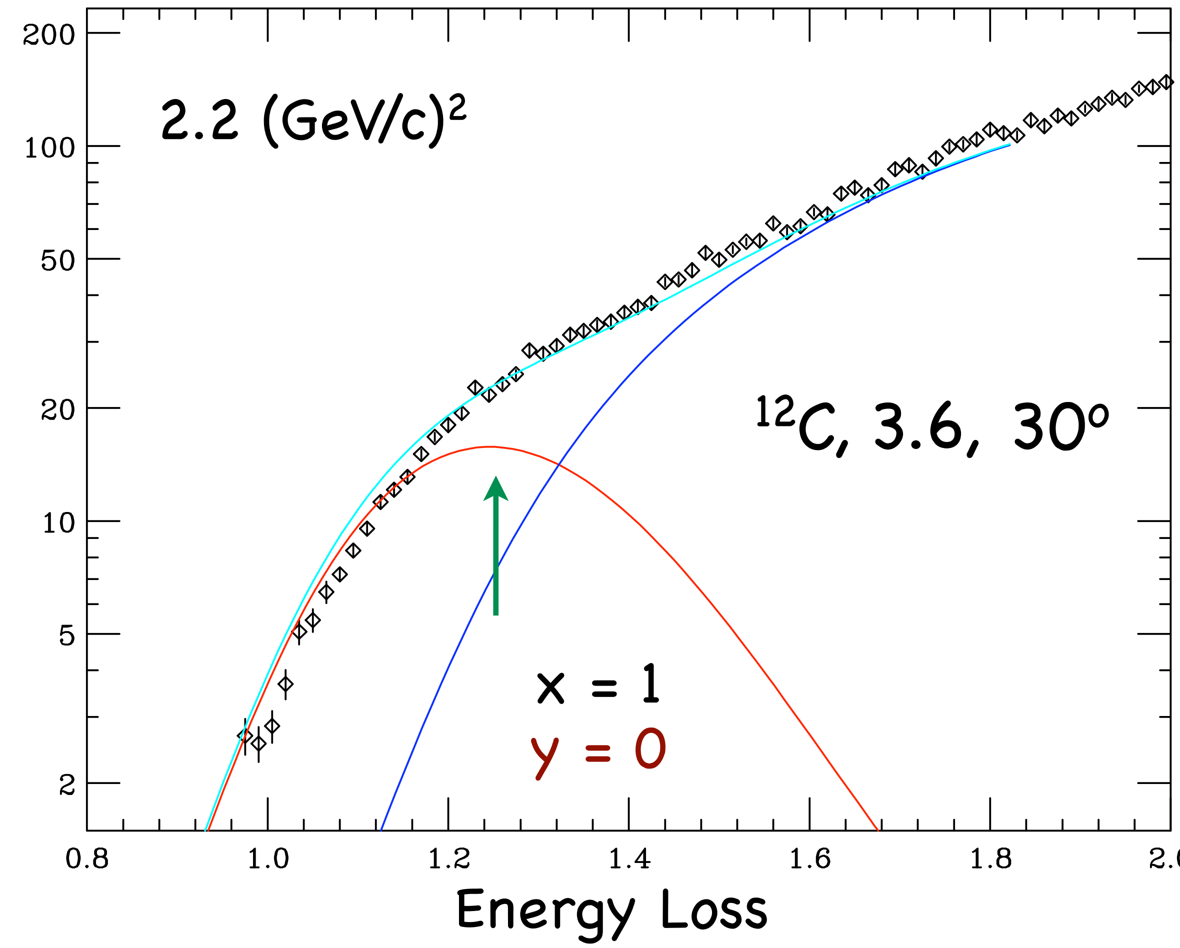


$$\Delta\omega = \sqrt{(\vec{k_f} + \vec{q})^2 + m^2} - \sqrt{(\vec{k_f} + \vec{q})^2 + m^2}$$

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

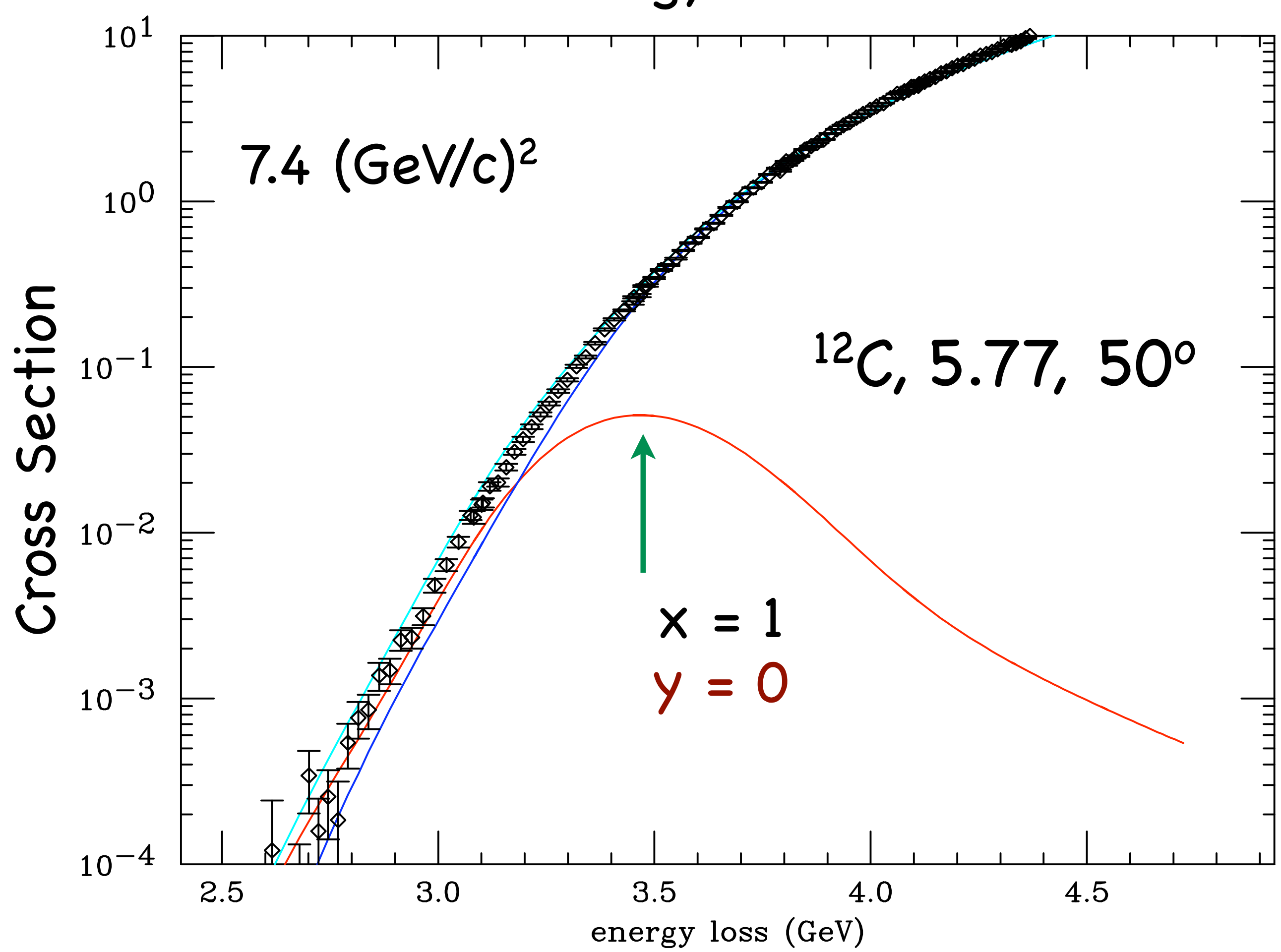
Inelastic contribution increases with Q^2





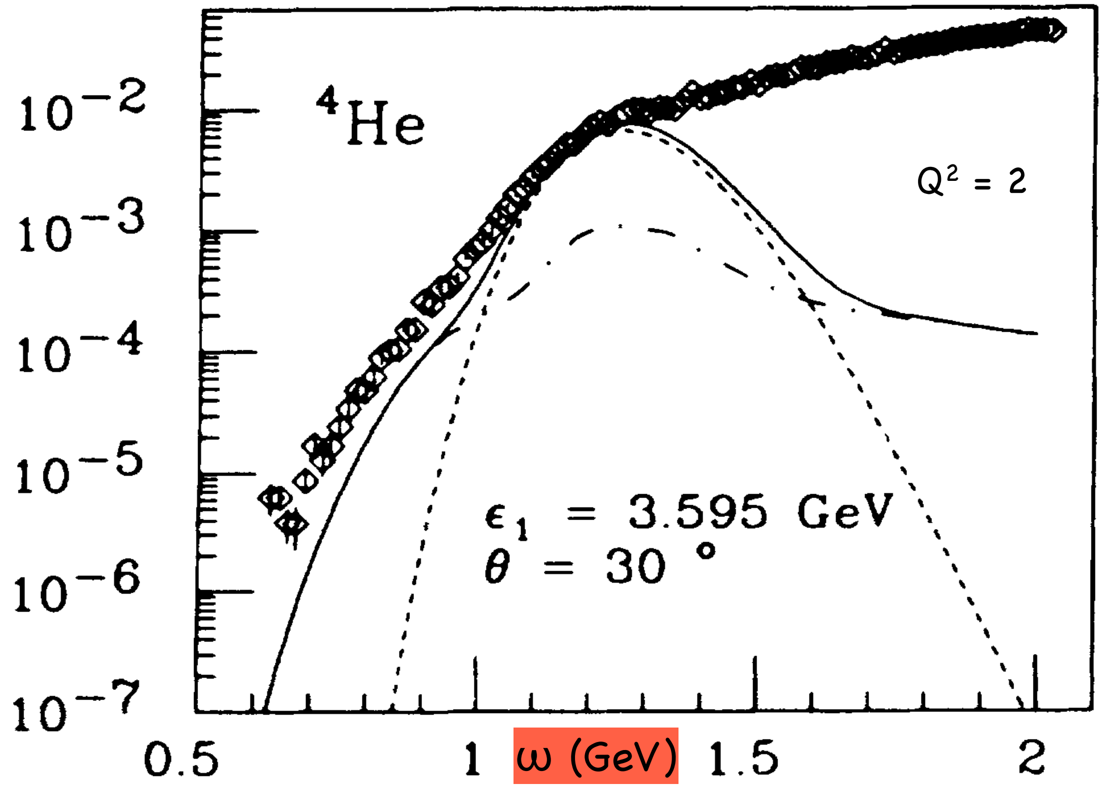
DIS begins to contribute at $x > 1$

Convolution model

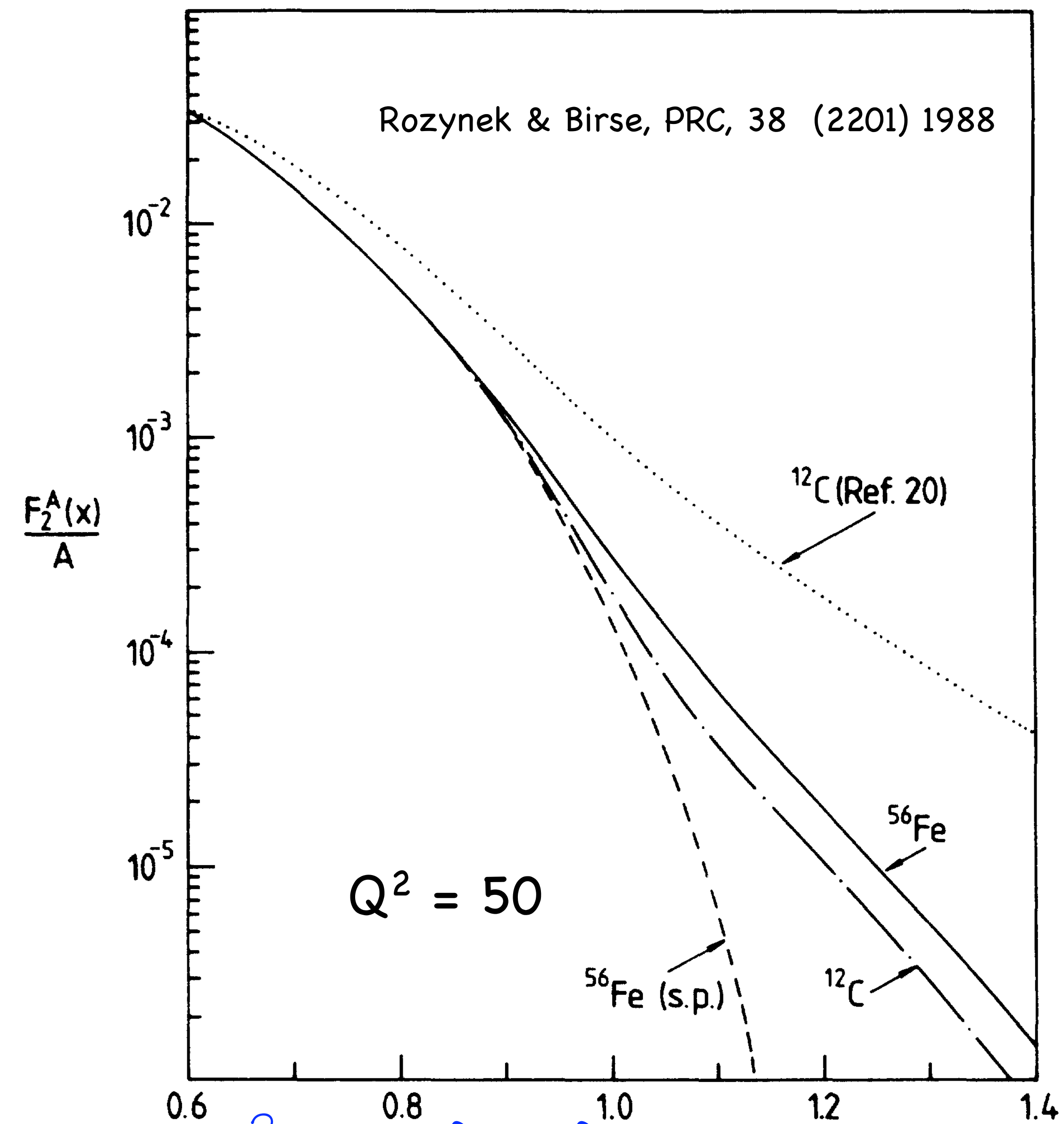


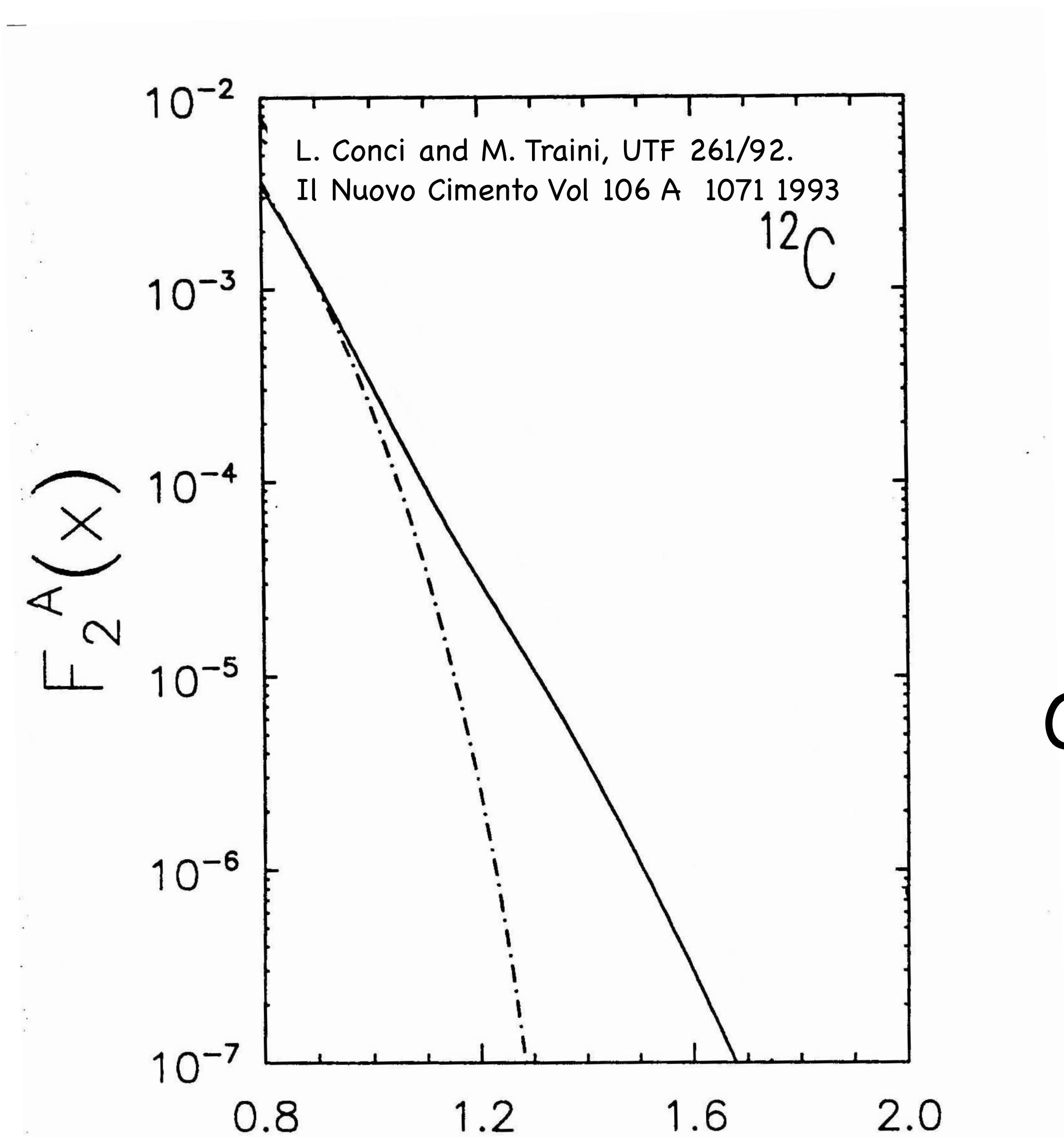
We expect that as Q^2 increases to see evidence for x-scaling - and Q^2 independence.

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



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



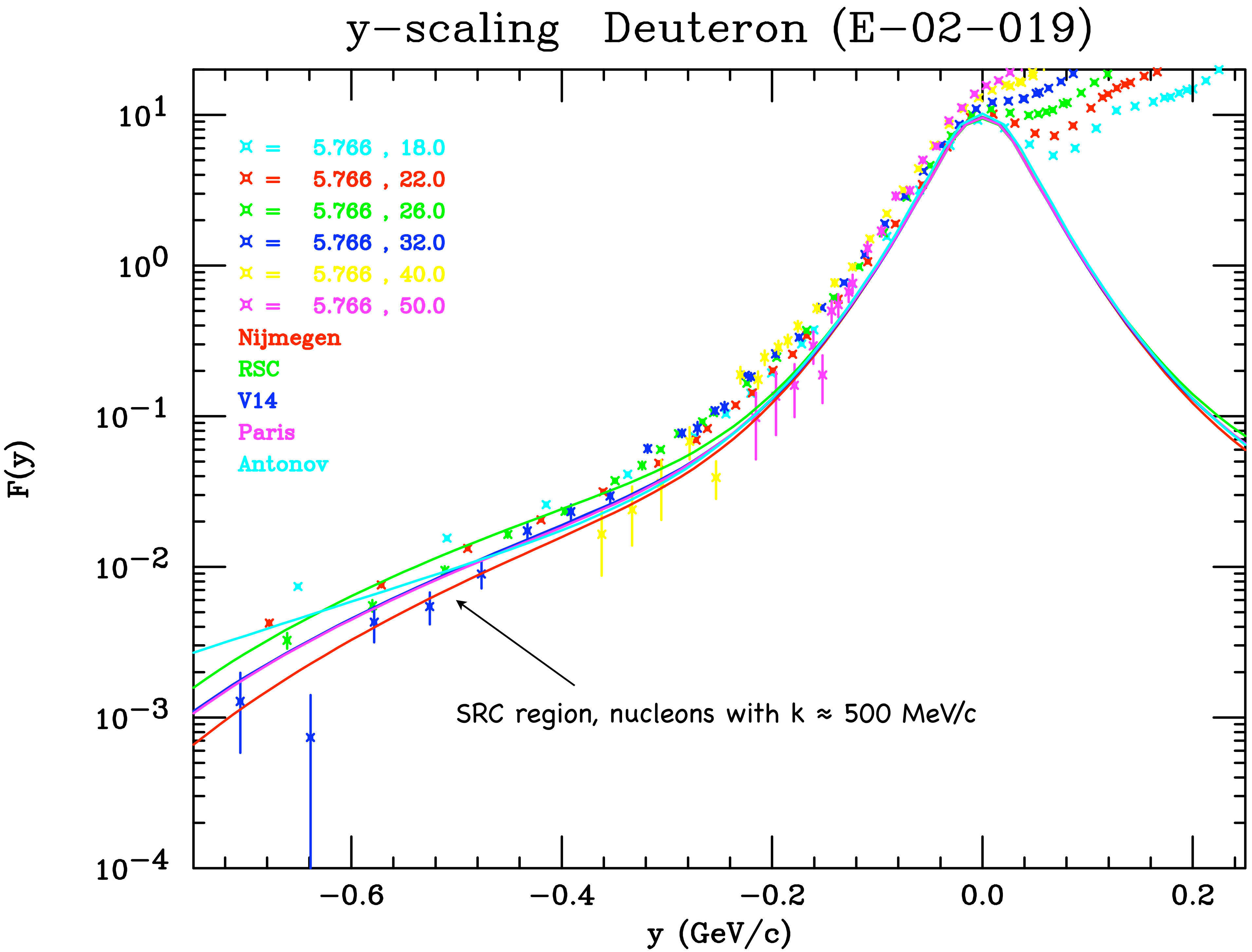


QES in IA

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

DIS

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



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.

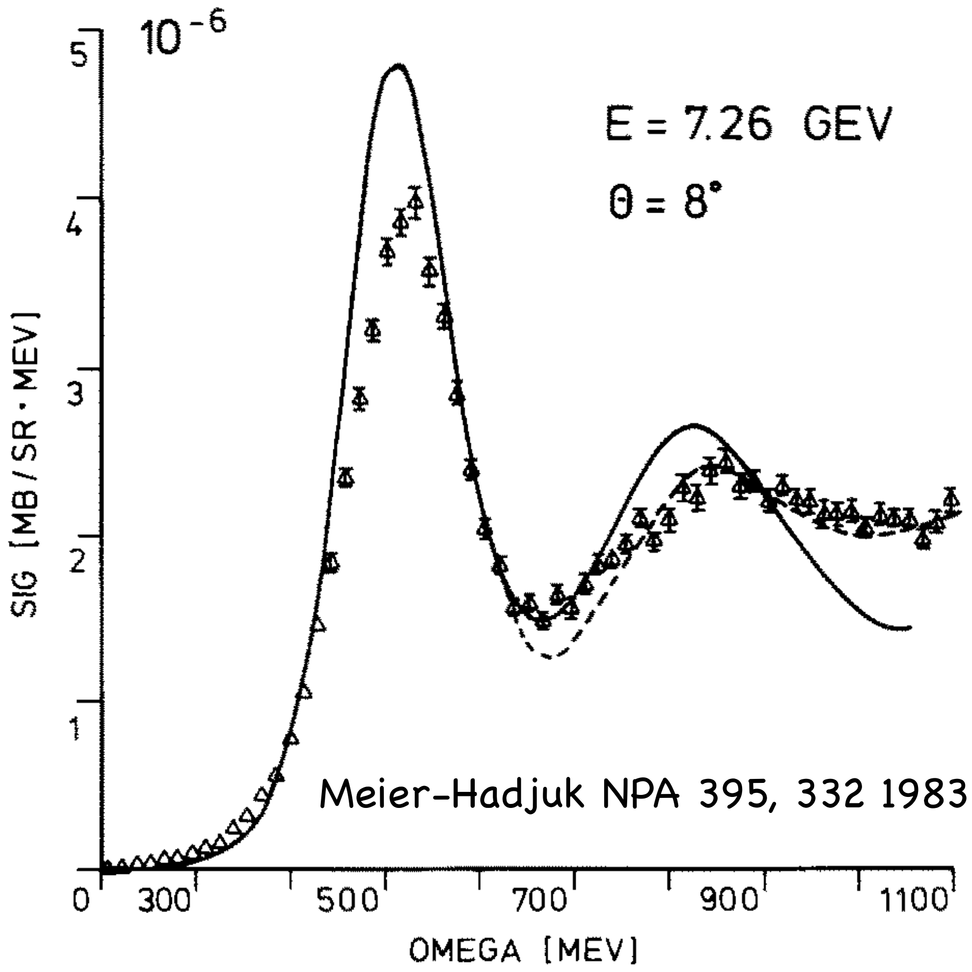
$$n(p) = -\frac{1}{2\pi y}\frac{dF(y)}{dy}$$

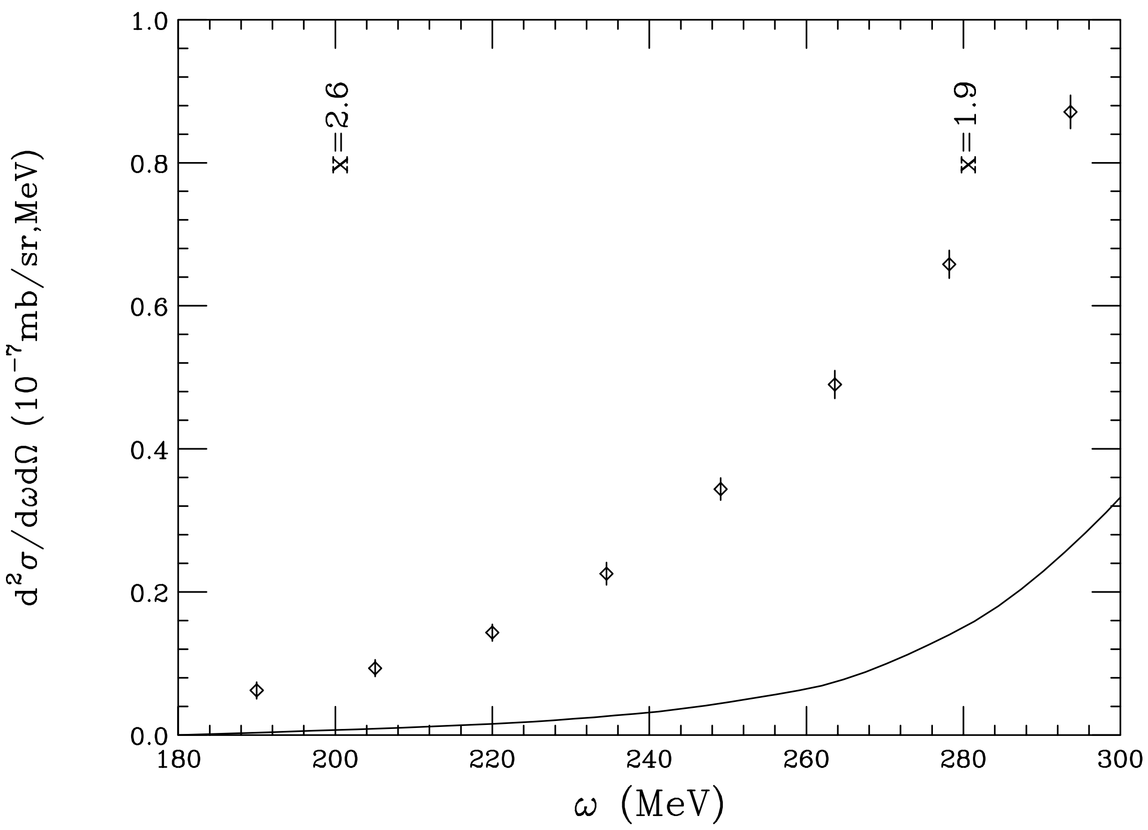
y is the momentum of the struck nucleon parallel to the momentum transfer: $y \approx -q/2 + m\nu/q$

What role FSI?

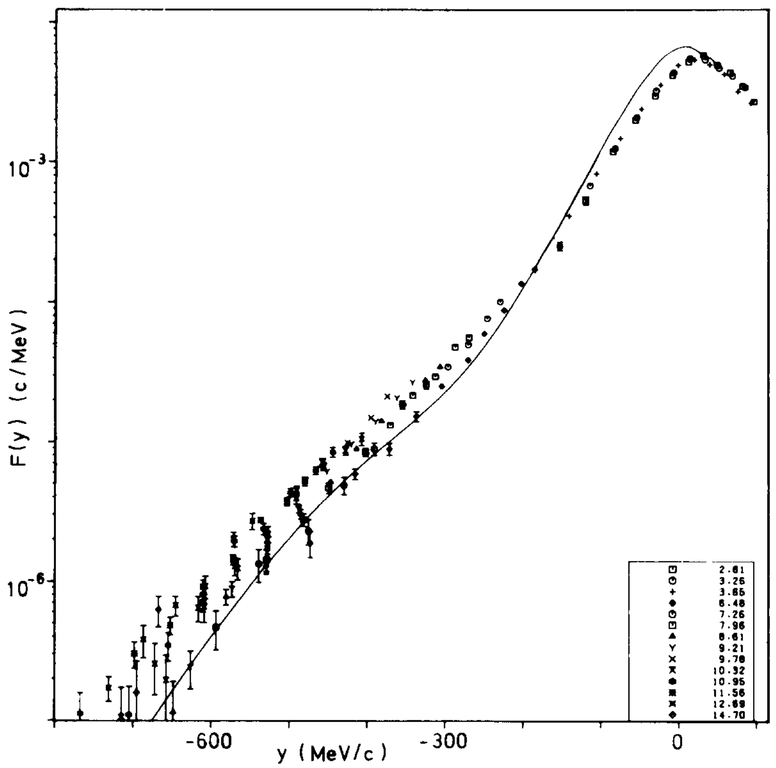
In (e,e′p) flux of outgoing protons strongly suppressed: 20-40% in C, 50-70% in Au

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





Failure of the spectral function or of PWIA indicating role of FSI?



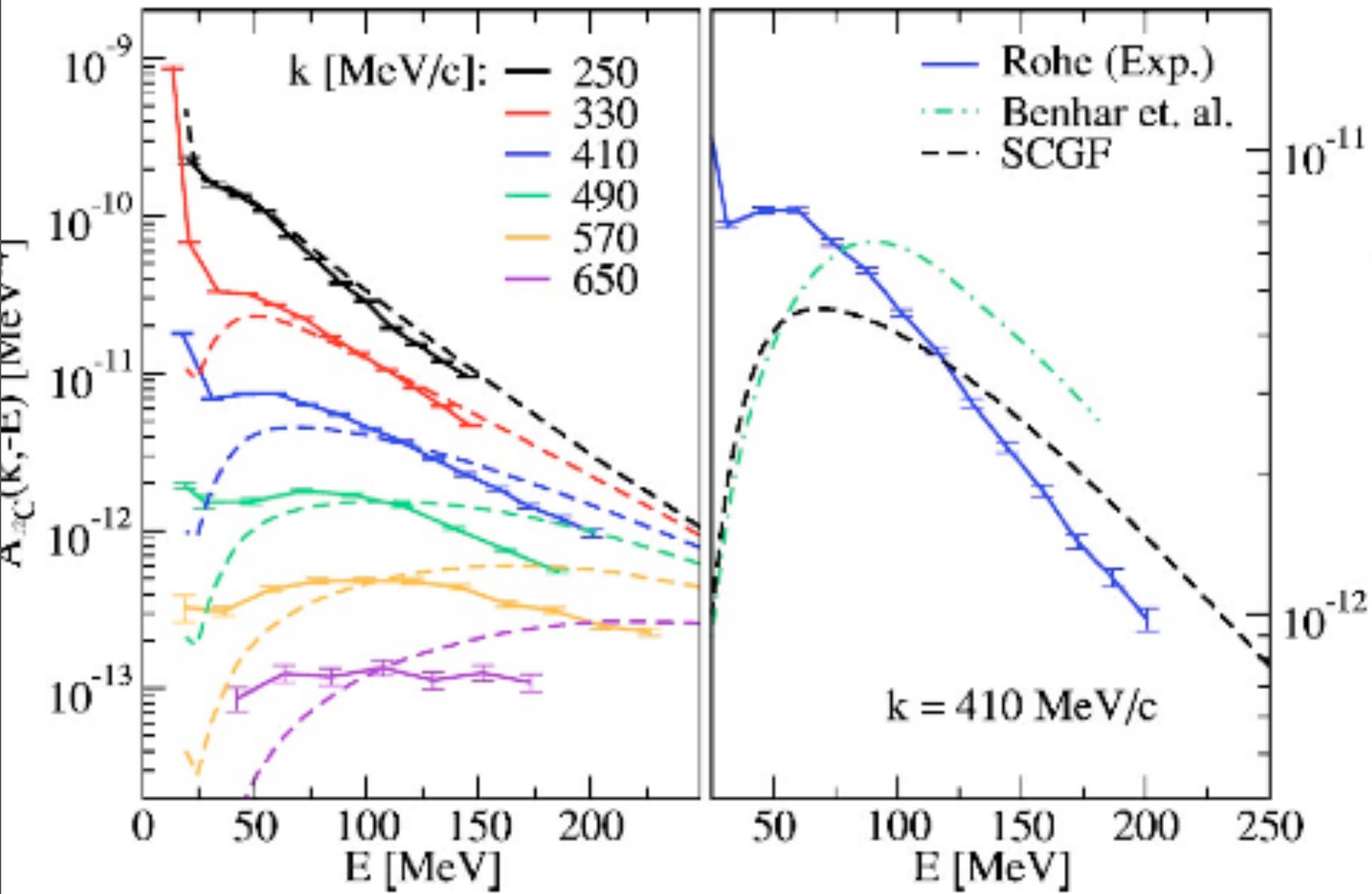
Meier-Hadjuk et alNuclearPhysicsA395 (1983) 332-348

^{3}He scaling experimental data and theory calculated such that most of the high-E is integrated over

One can make arguments …

- RSC - lead to smaller correlation effects
- Redistribution of strength in E can account for the difference
- Such a proposal has been made by:
  - C. degli Atti, E. Pace, and G. Salme, Phys. Lett. B127 (1983) 303 and
  - DD in Proceedings of the Two Nucleon Emission Workshop, Elba 1989, (Benhar and Fabrocini, Eds).
- Data from JLab suggest as much

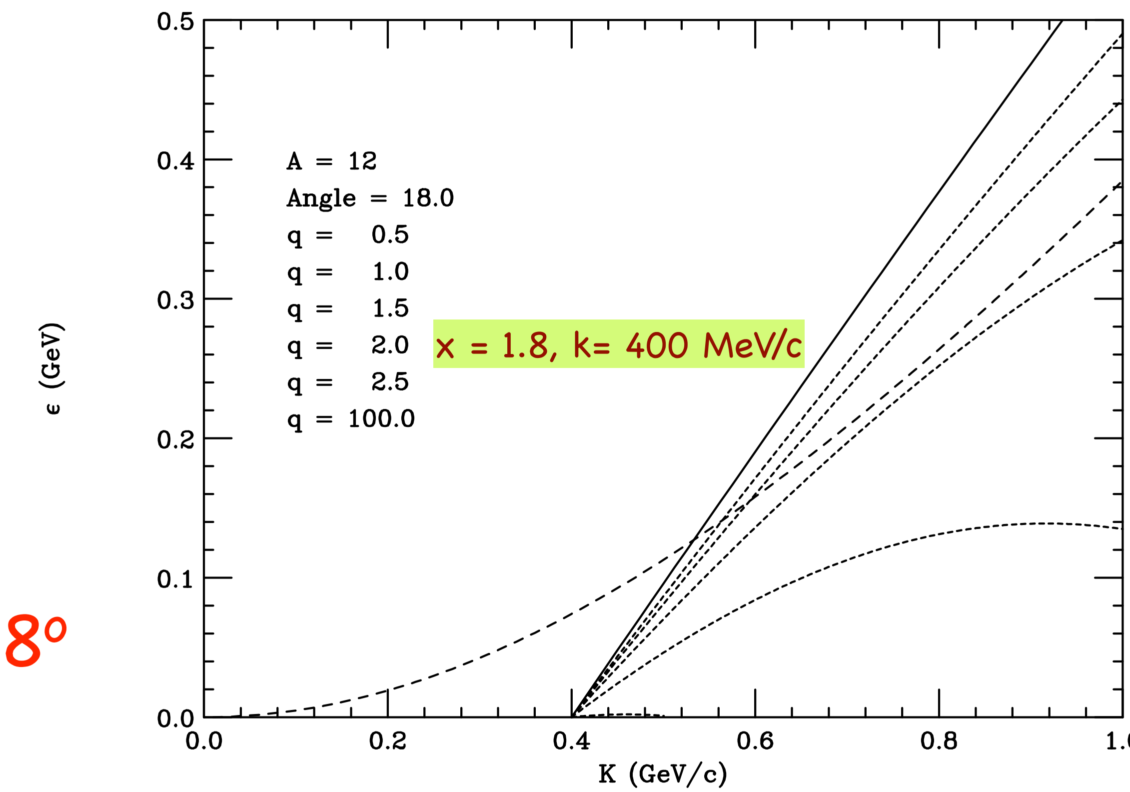
JLab data on ^{12}C (e,e′p) of Rohe et al.



Data suggests more strength at smaller E – accessible at large x

Frick et al. PRC 70, 024309 (2004)

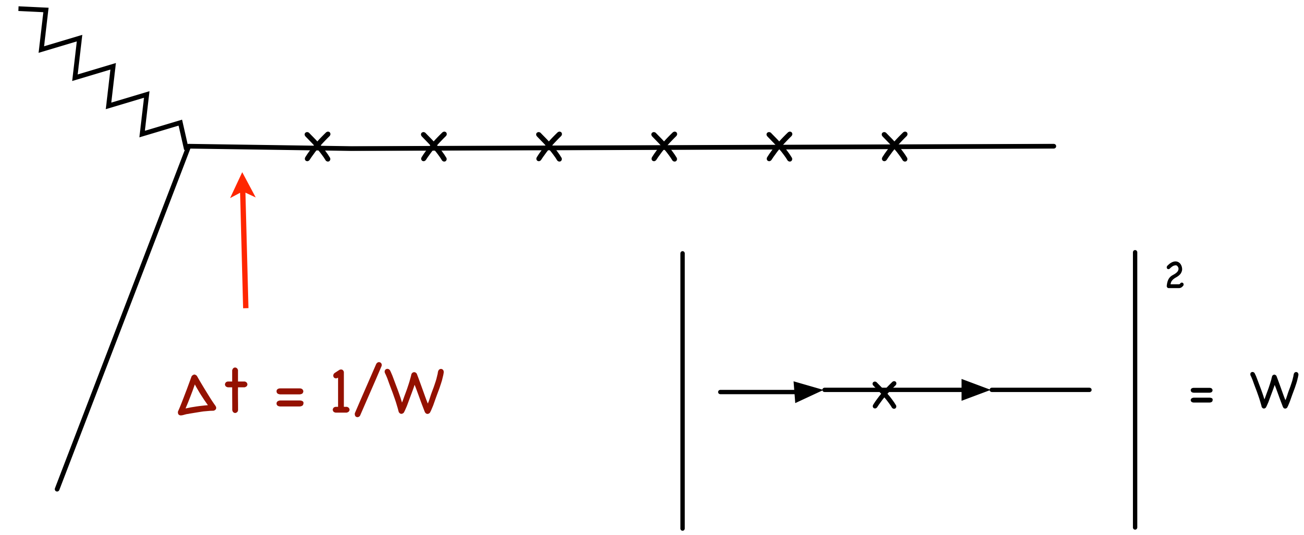
Self consistent Greens Function (SGGF)



Integration limits (e,e′) Carbon 18°

FSI in QES.

Take V and W to be the real and imaginary parts of the optical potential of a nucleon in nuclear matter.



V can be ignored (~20 MeV) compared to the 100s of MeV here

V is small and the dominant part comes from the "damping" of the motion of the struck nucleon by the imaginary potential W

$$W^A_{\mu\nu}(q,\omega) = \int_0^\infty d\omega' F(\omega-\omega') W^A_{\mu\nu,IA}(q,\omega' - V(q))$$

folding function

$$F(\omega-\omega') = \frac{1}{\pi}\Re\int_0^\infty dt\; e^{i(\omega-\omega')t}\, e^{-W(q,t)t}$$

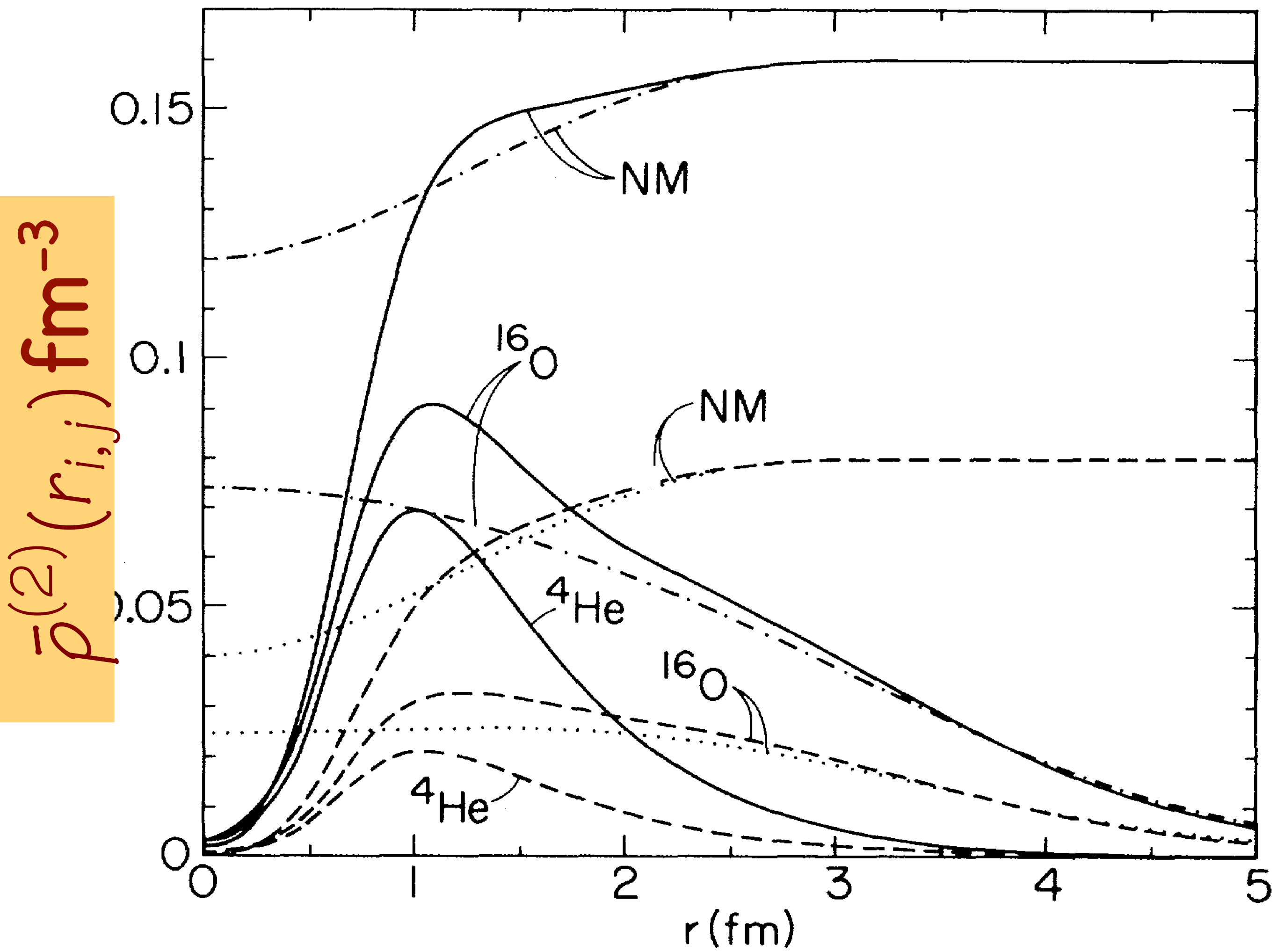
If W = 0 then $F(\omega - \omega')$ becomes δ function and $W_{\mu\nu}{}^A \Rightarrow W_{\mu\nu,IA}{}^A$

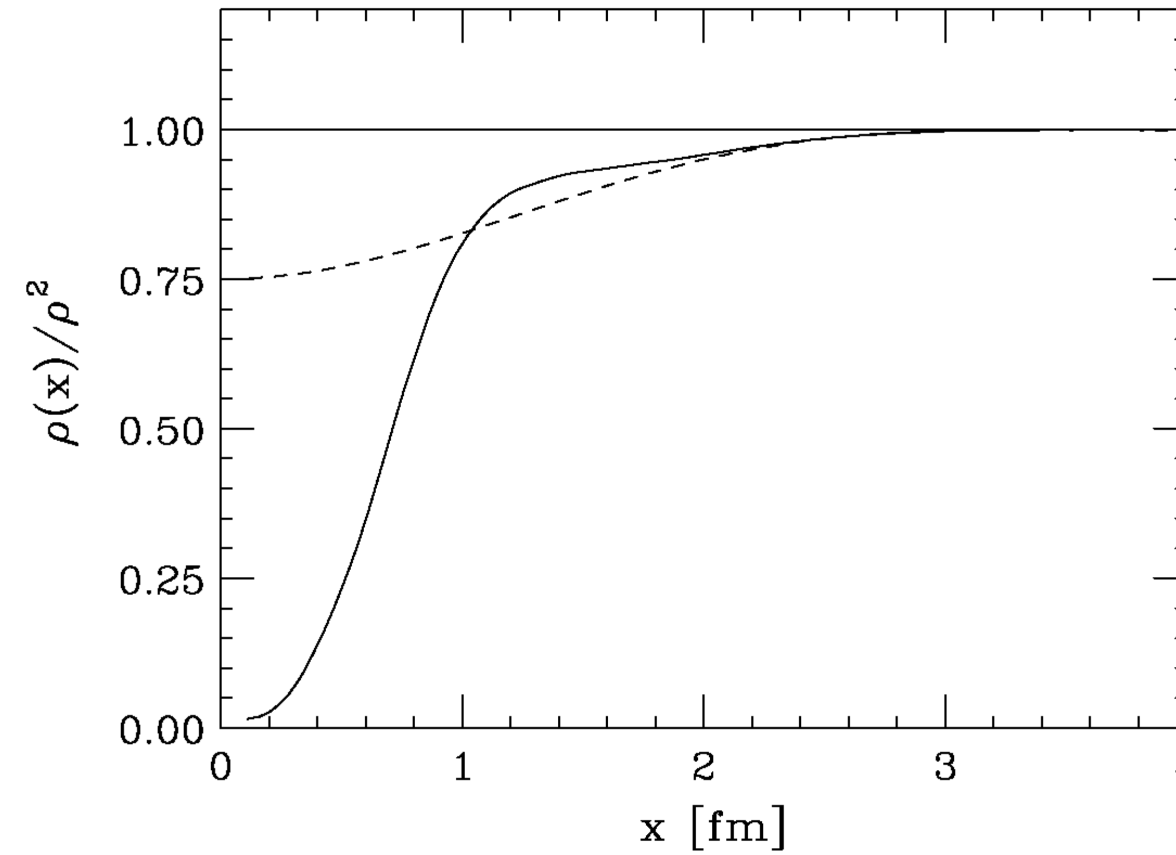
Imaginary part of optical potential

$$W(p') = \frac{\hbar}{2}\rho v(p')\sigma_{NN}(p')$$

density

Rescattering depends on joint probability of finding the struck particle at position r_i and a spectator at position r_j $\rho^{(2)}(r_i, r_j) = \rho_A(r_i)\rho_A(r_j)g(r_i, r_j)$



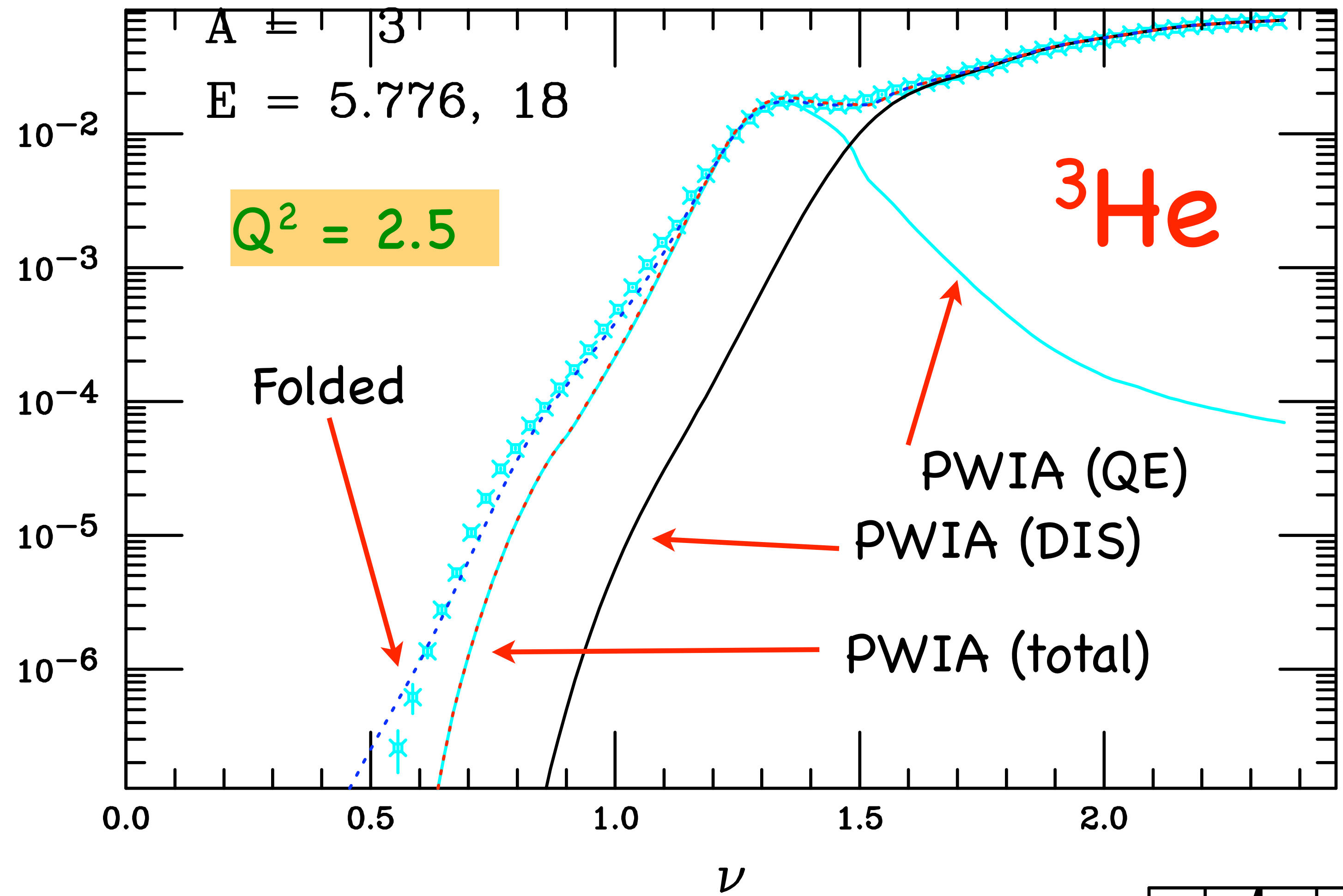


$$\bar{\rho}^{(2)}(r_{i,j}) = \frac{1}{A}\int d^3R_{ij}\rho^{(2)}(r_i, r_j)$$

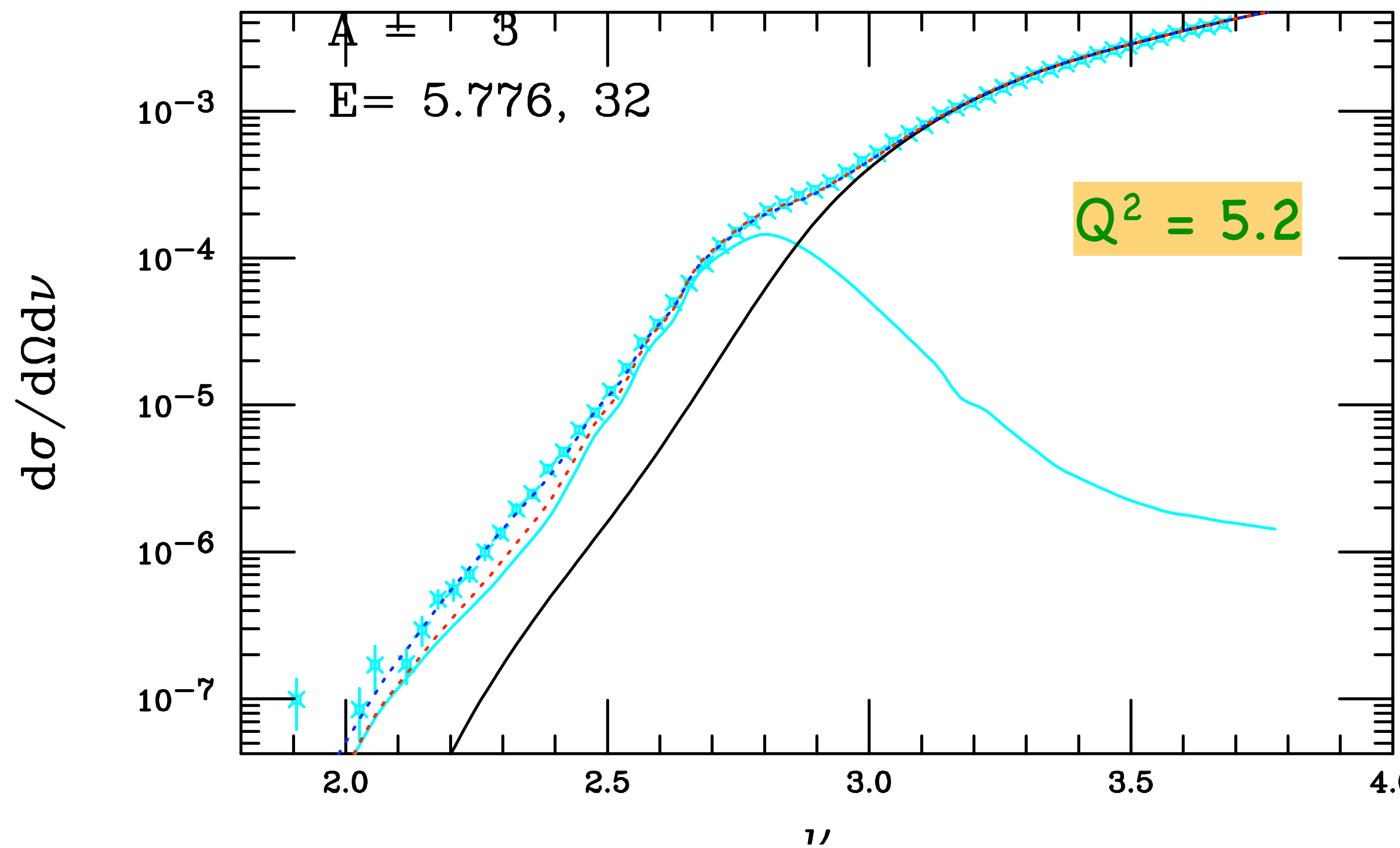
SRC suppress FSI

If density is 0, the motion is undamped

Final State Interactions in CGA



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



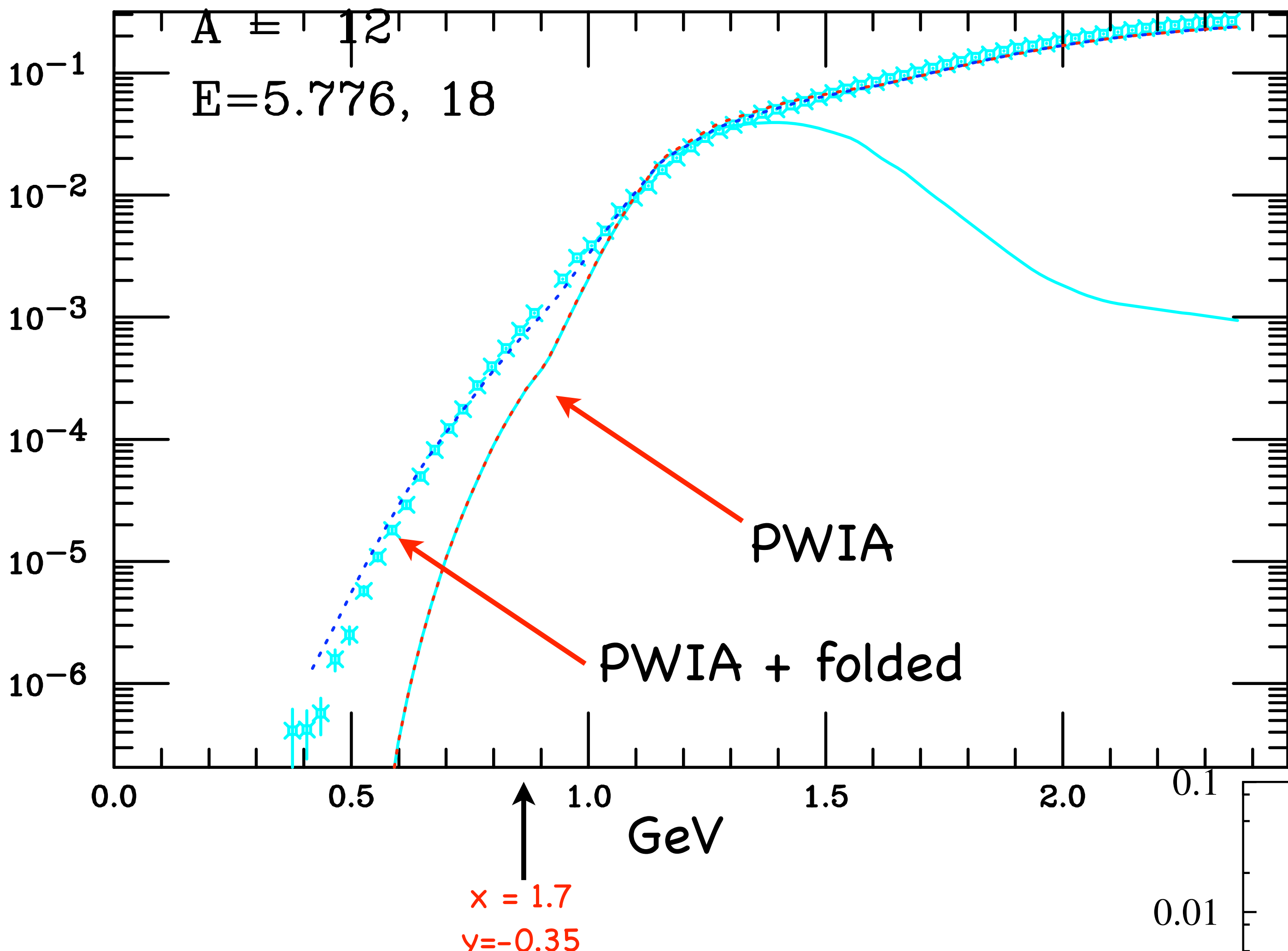
Benhar et al. PRC 44, 2328

Benhar, Pandharipande, PRC 47, 2218

Benhar et al. PLB 3443, 47

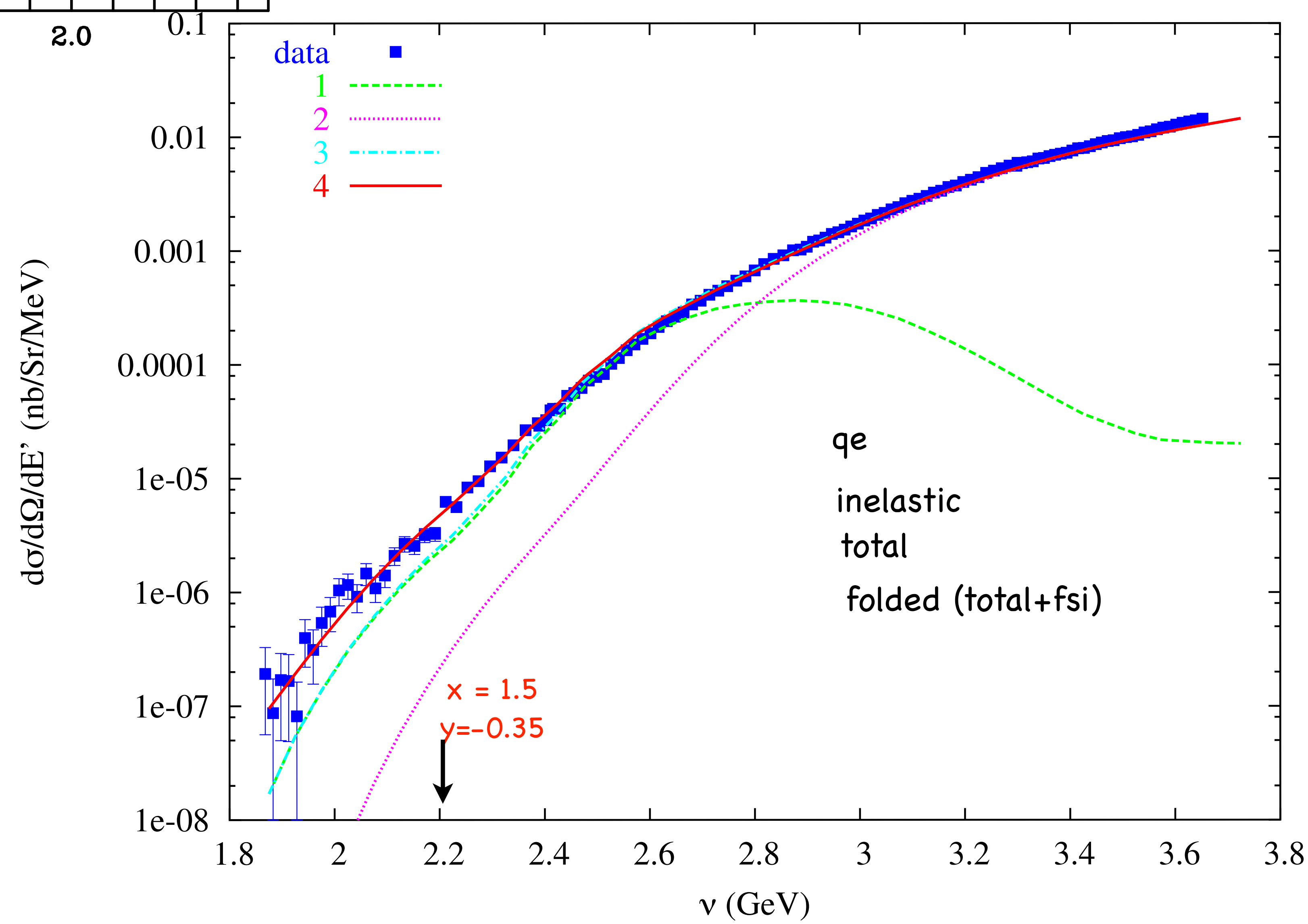
O. Benhar private comm.

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

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O. Benhar private comm.

Sensitivity to g(r)

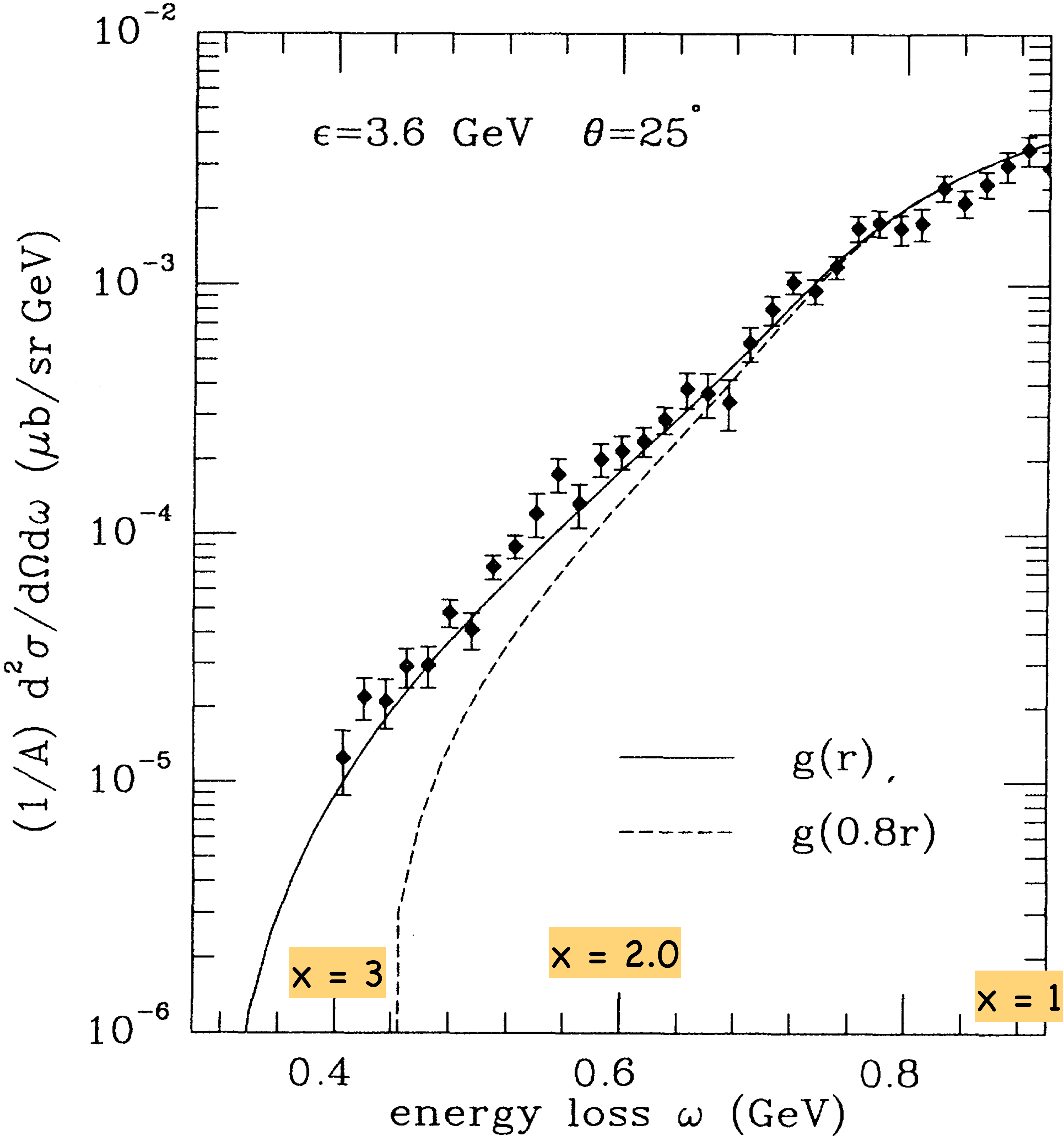
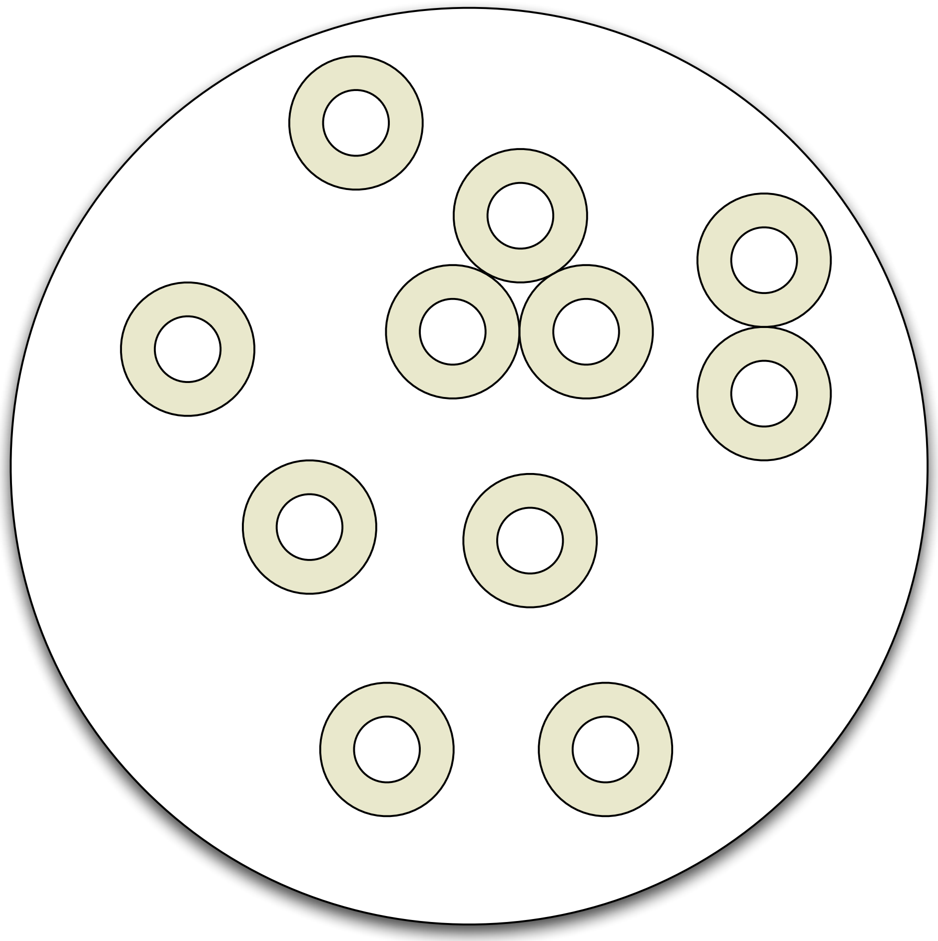


FIG. 13. Sensitivity of the inclusive cross section to the *N*-*N* pair distribution function at ϵ=3.6 GeV and θ=25°.

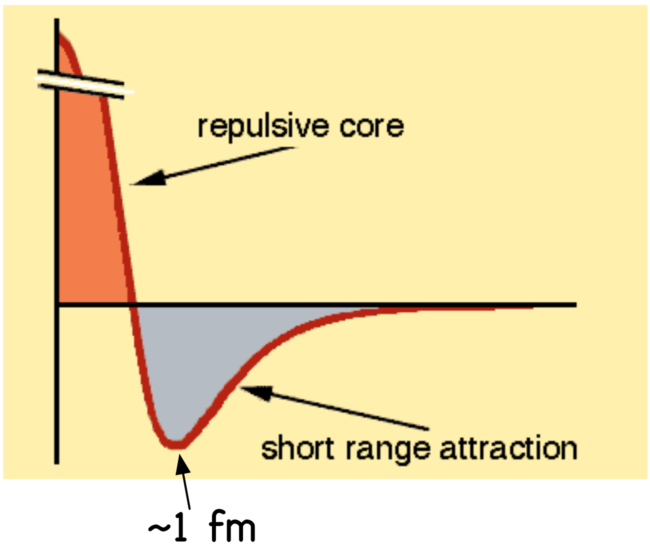
Issues about FSI

- Extreme sensitivity to hole size
- On-shell cross sections: nucleon is off-shell by in E by hbar/Δt = hbar W
- total cross section?
- Unitarity?   Folding function is normalized to one.
- Role of momentum dependent folding function (Petraki etal, PRC 67 014605) has lead to a quenching of the tails.
    - Comparison to data with this new model would be useful
- Reasonable but what is the error band on the results?

What I do not understand about FSI in QES.



Exclusion zone surrounds every nucleon



electron is sensitive to a region r ~ 1/q around the vertex

for q = 1 GeV/c, r ~ 0.2fm

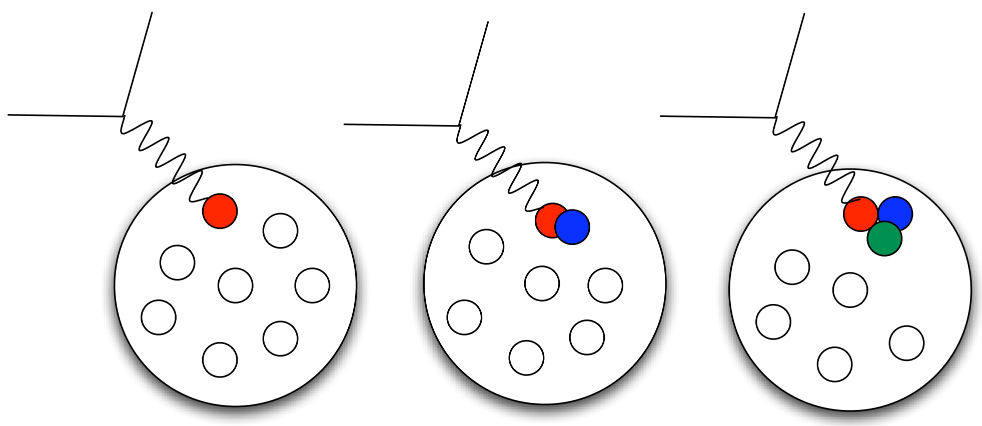
the 'hole' is about that large

What is the range of the FSI?

If FSI are restricted to the region of the hole then $FSI^{A>>} = FSI^{A=2}$

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.

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

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

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

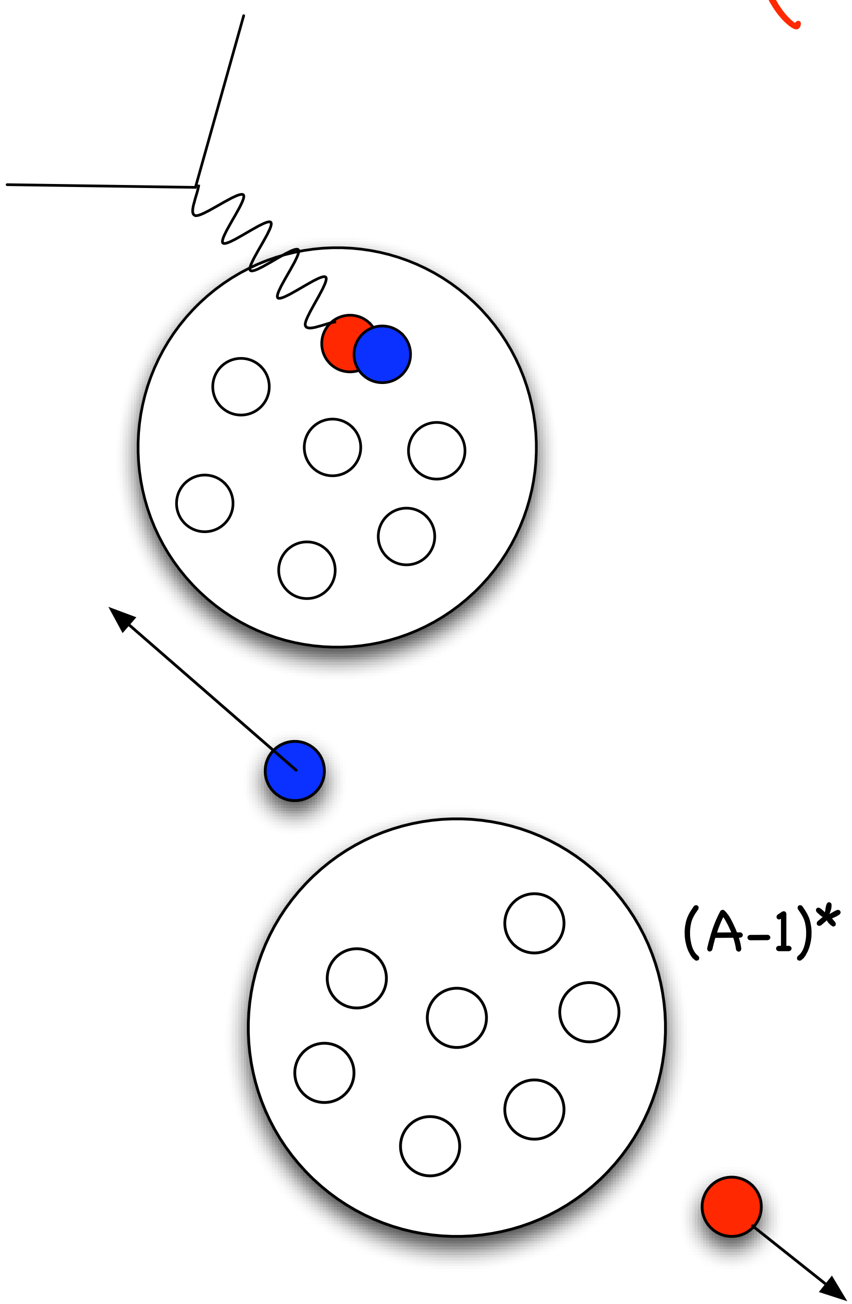
In the ratios, off-shell effects and FSI largely cancel.

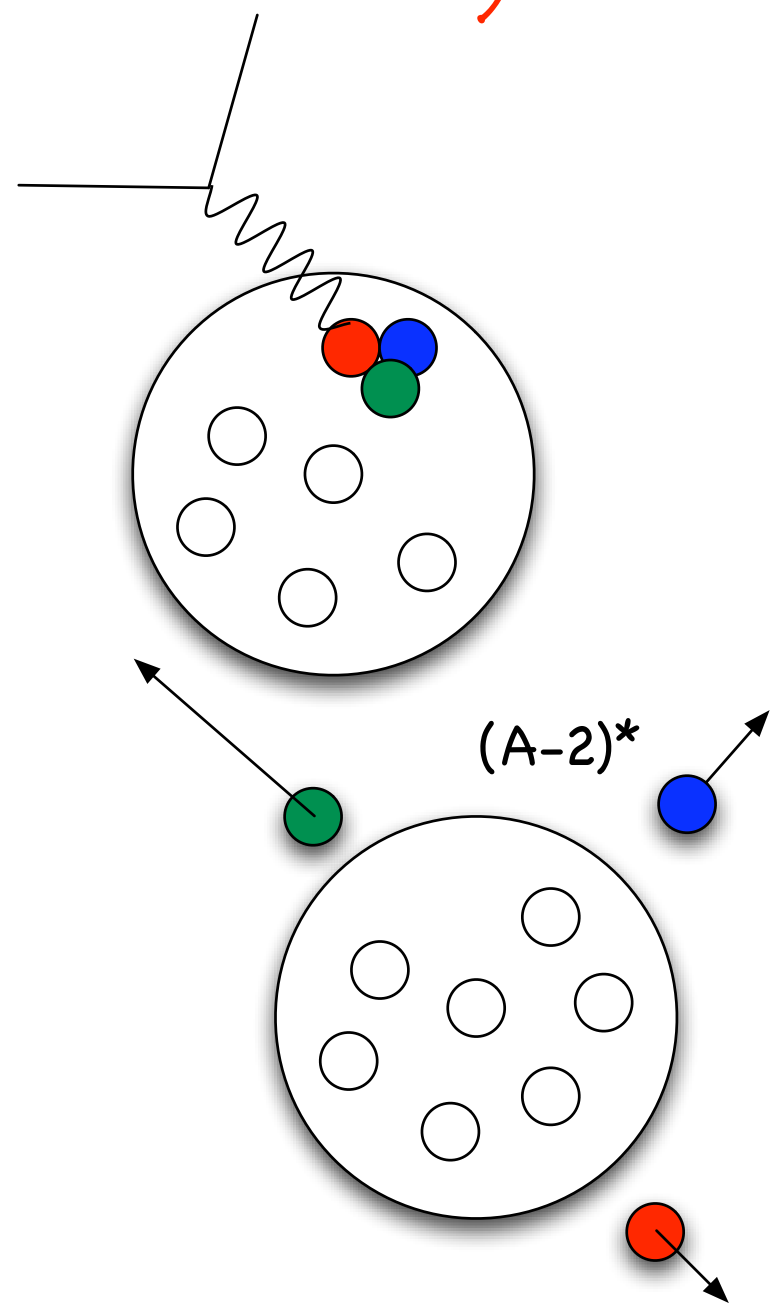
$a_j(A)$ is proportional to probability of finding a j-nucleon correlation

Knocking out a nucleon in a two-nucleon pair

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

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





$F_2(\alpha_{tn})$

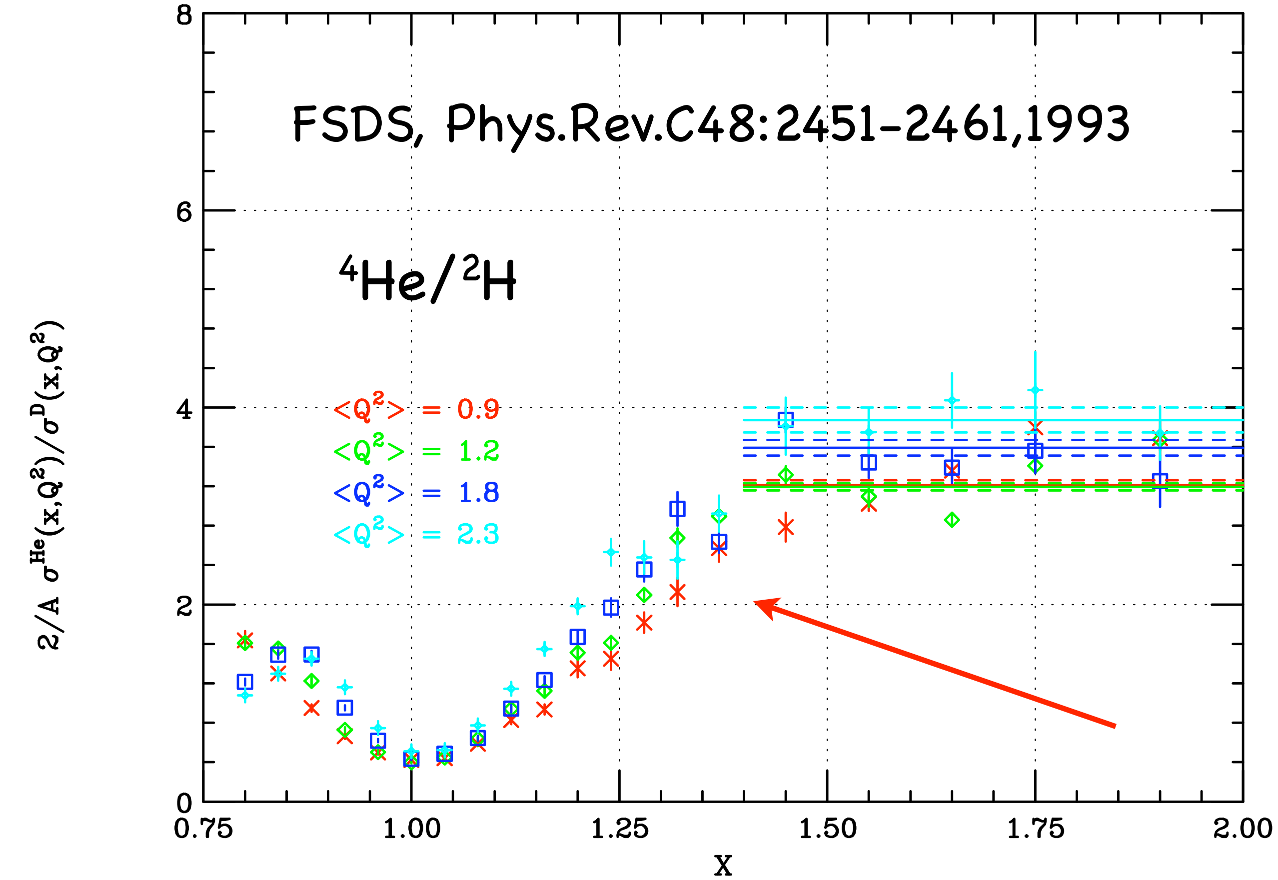
Ratios

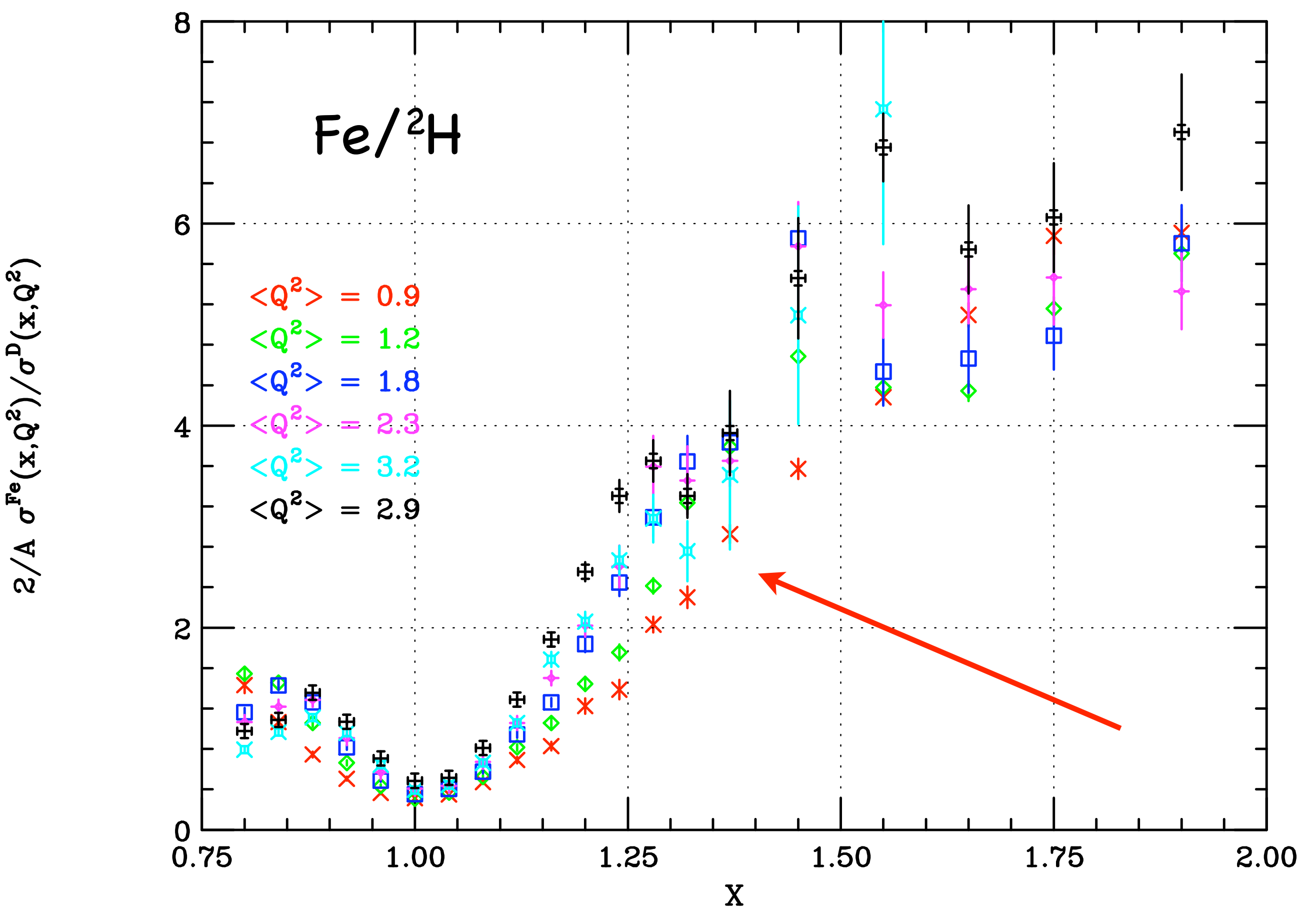
Accounts for Q^2 dependence

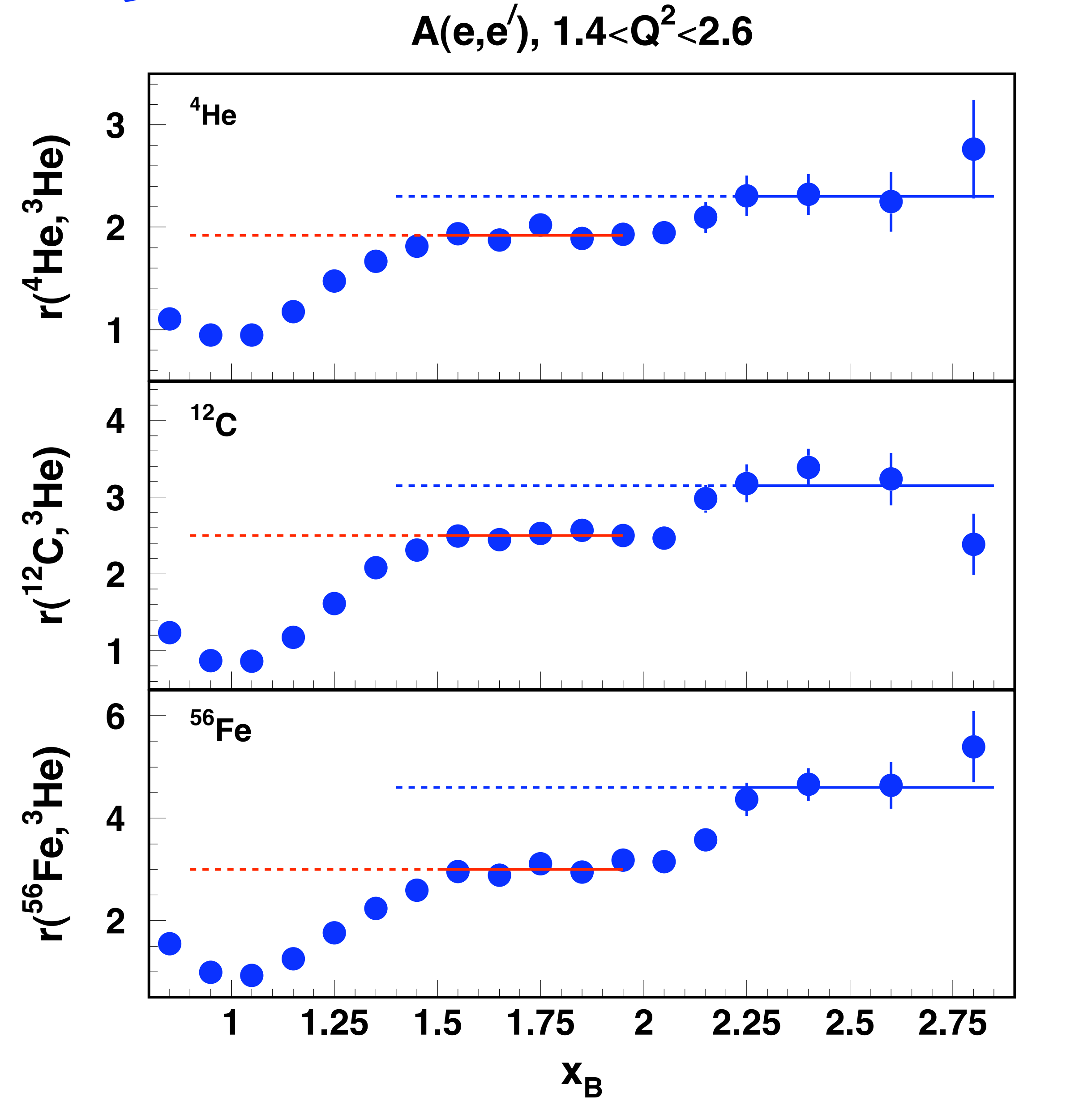
FSDS, Phys.Rev.C48:2451-2461,1993

Ratios, SRC's and Q^2 scaling

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



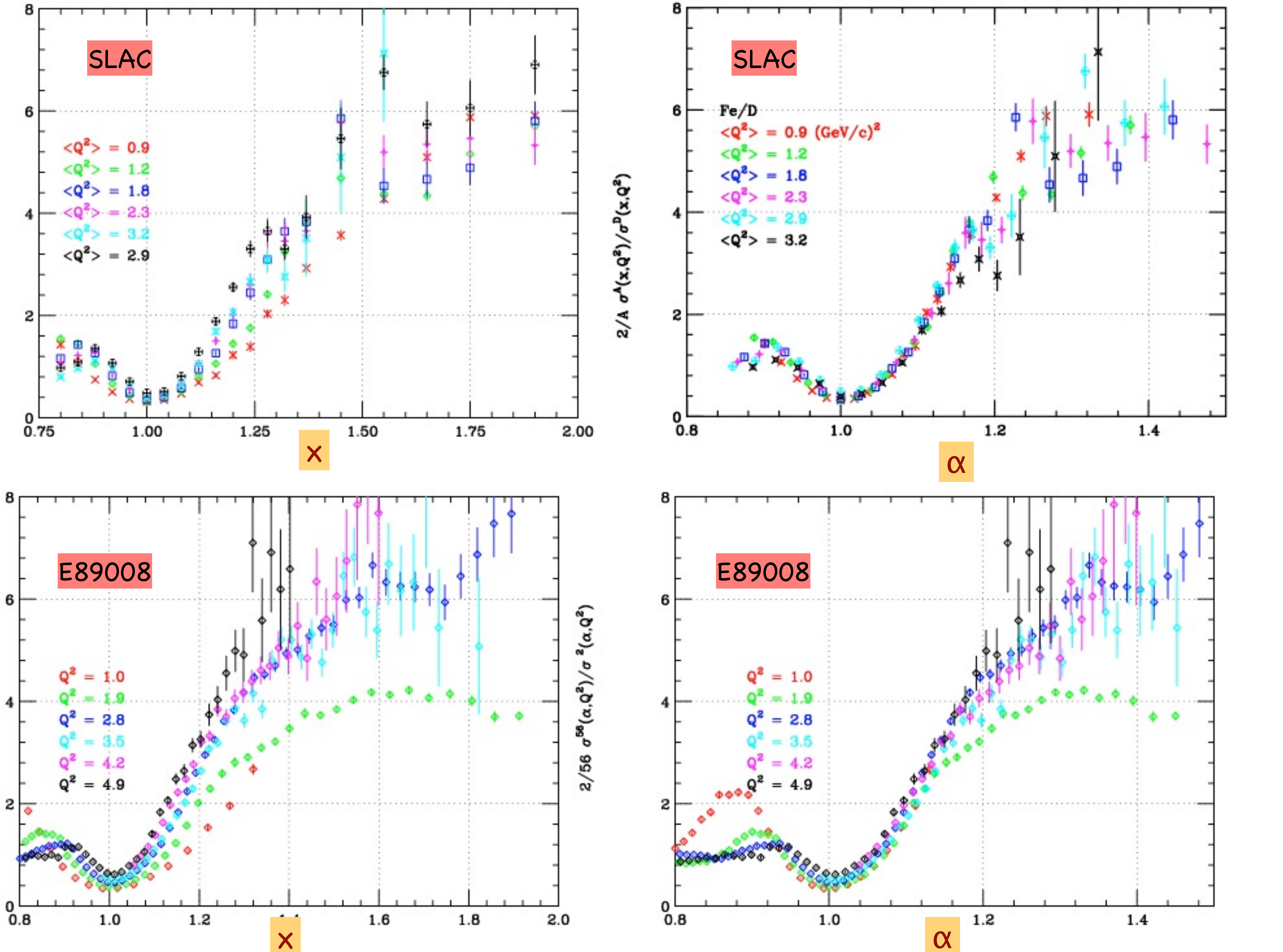


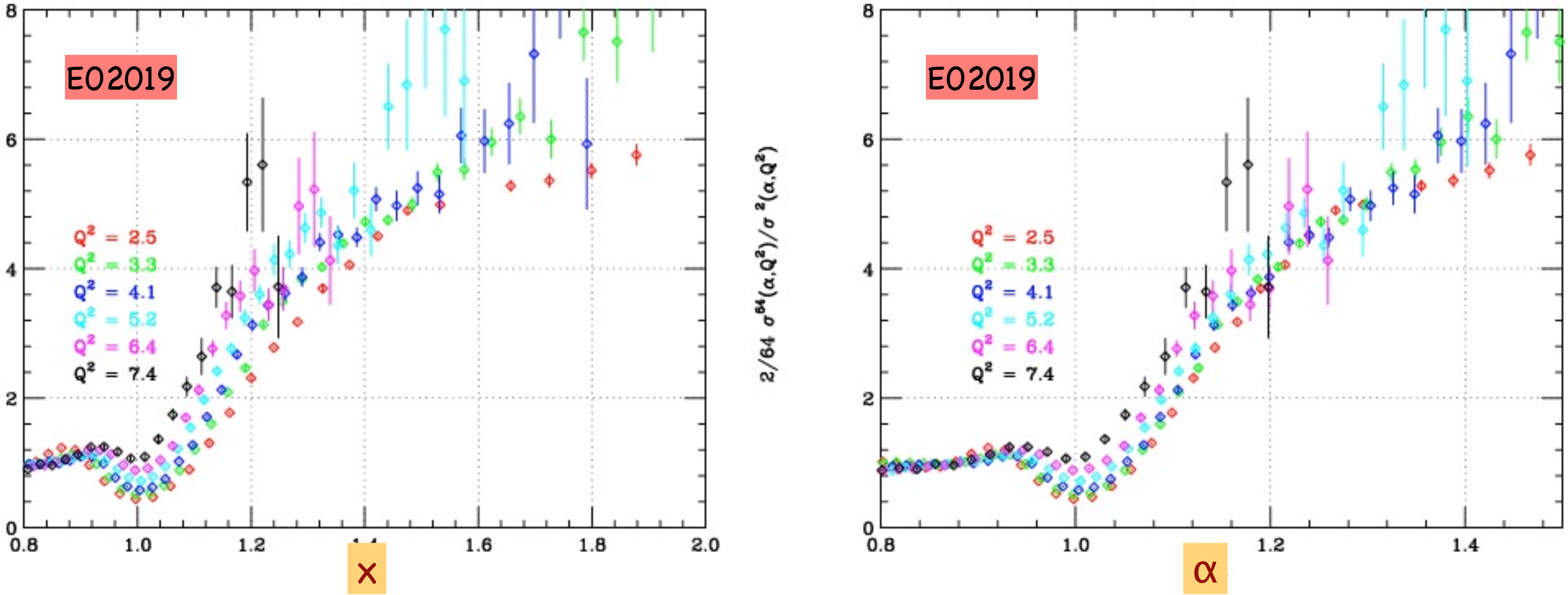


$\alpha_{2N} \approx 20\%$
$\alpha_{3N} \approx 1\%$

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

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

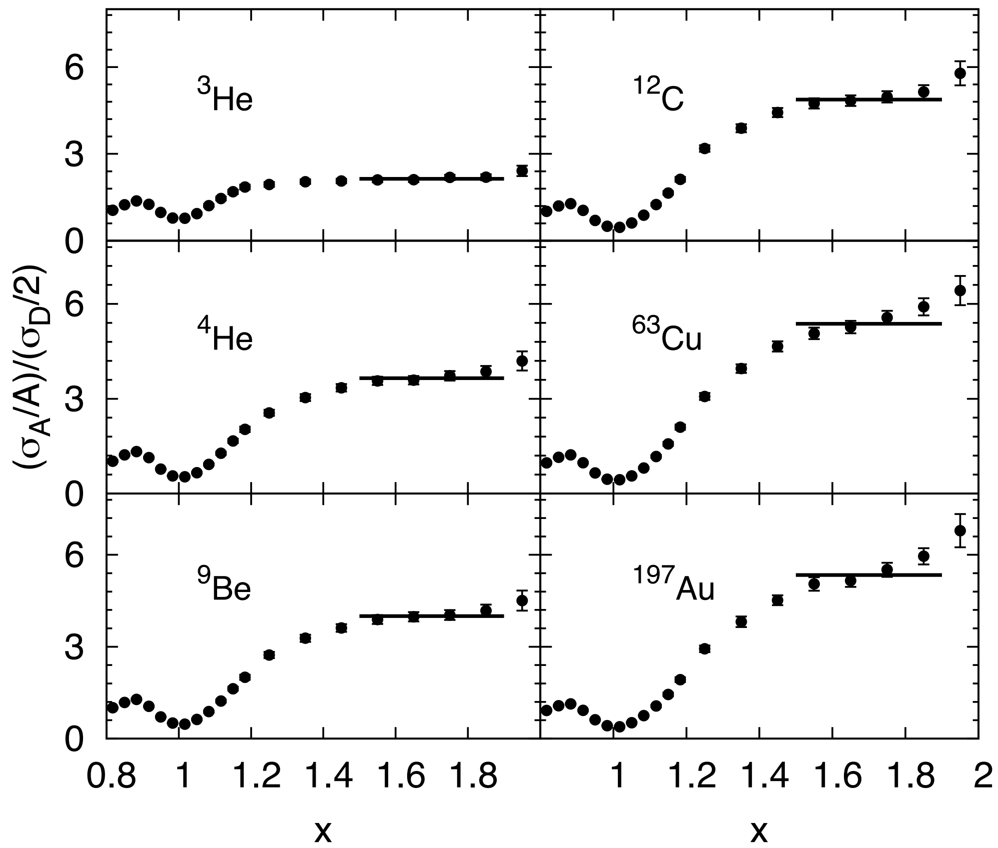

SLAC
<Q²> = 0.9
<Q²> = 1.2
<Q²> = 1.8
<Q²> = 2.3
<Q²> = 3.2
<Q²> = 2.9
x
SLAC
Fe/D
<Q²> = 0.9 (GeV/c)²
<Q²> = 1.2
<Q²> = 1.8
<Q²> = 2.3
<Q²> = 2.9
<Q²> = 3.2
2/A σ^A(x,Q²)/σ^D(x,Q²)
α
E89008
Q² = 1.0
Q² = 1.9
Q² = 2.8
Q² = 3.5
Q² = 4.2
Q² = 4.9
x
E89008
Q² = 1.0
Q² = 1.9
Q² = 2.8
Q² = 3.5
Q² = 4.2
Q² = 4.9
2/56 σ^56(α,Q²)/σ ²(α,Q²)
α

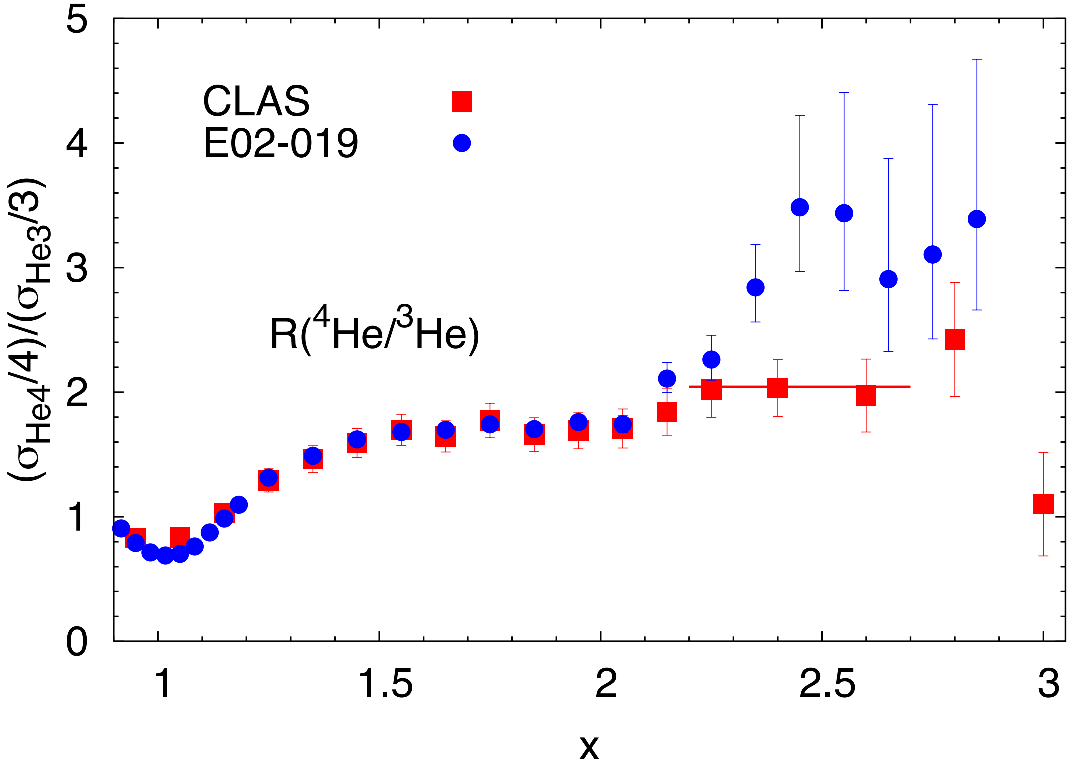


As can be seen the ratio at x = 1 (α = 1) increases with Q^2 because of inelastic processes, spoiling the scaling with α

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

N. Fomin just showed these

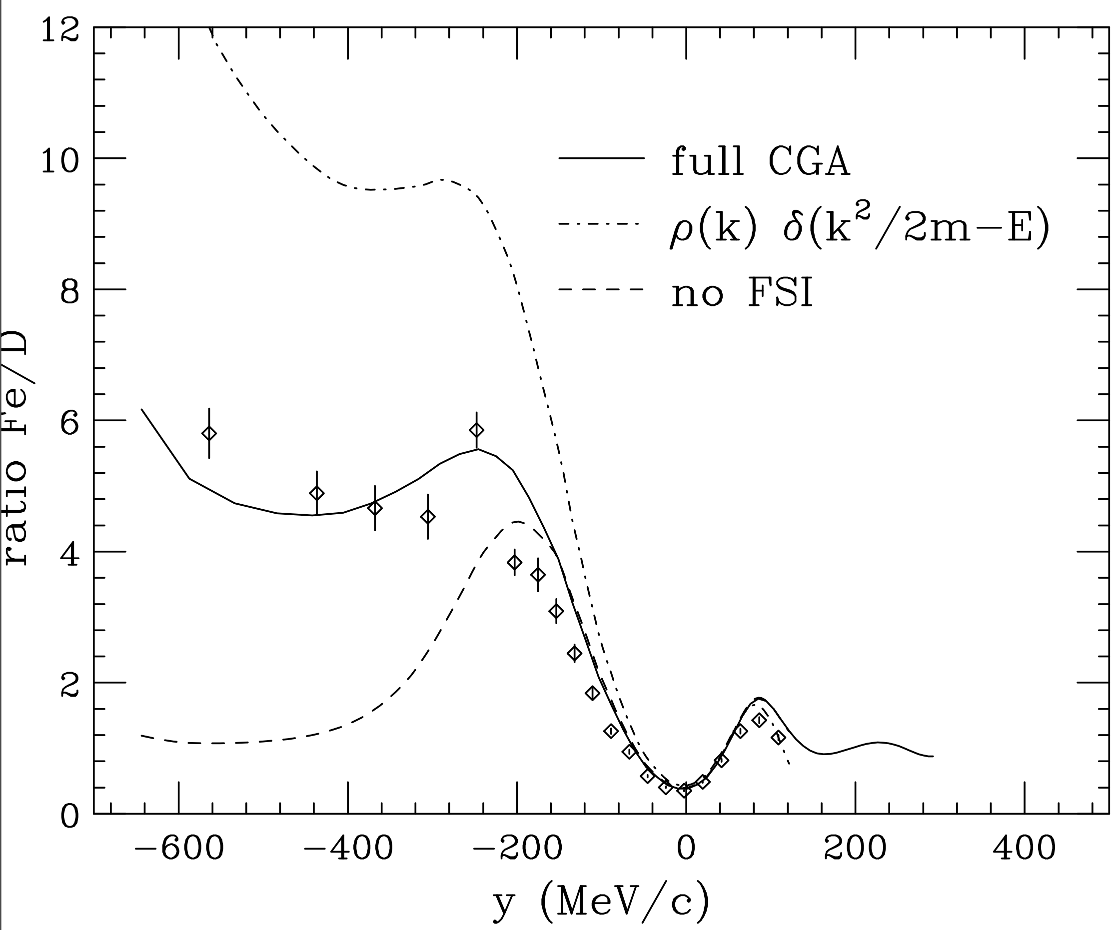




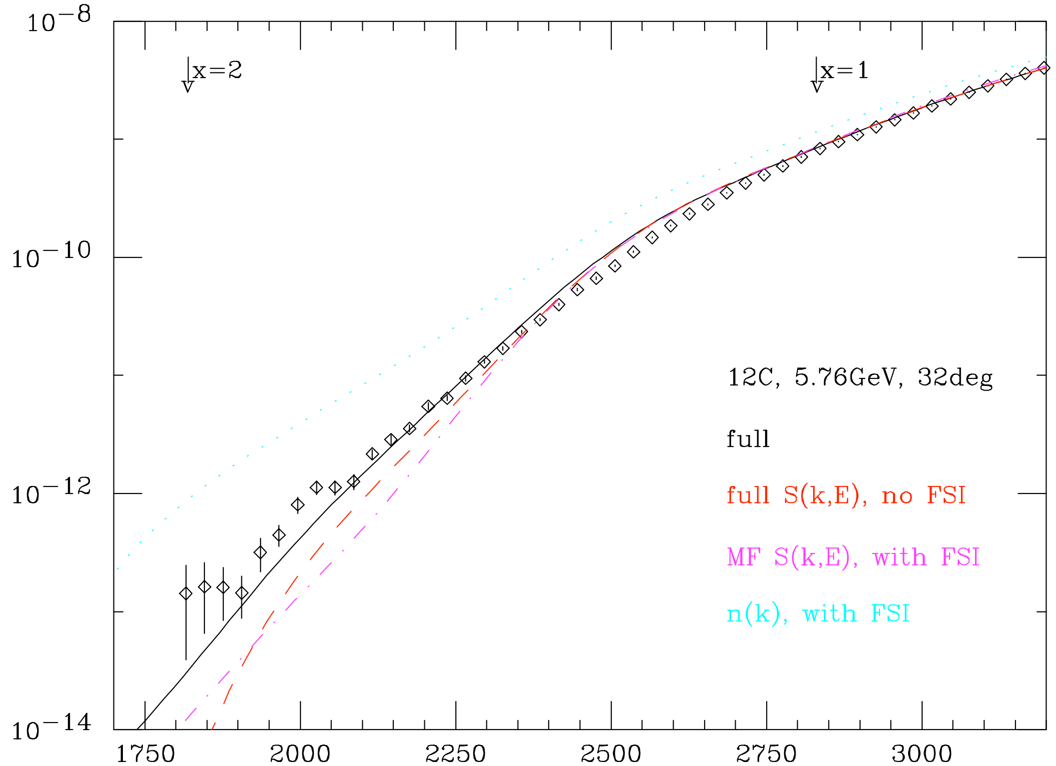
Emphatic arguments have been made that these ratio values are an artifact - can not be interpreted as the ratio of correlated in strength in heavy to light nuclei

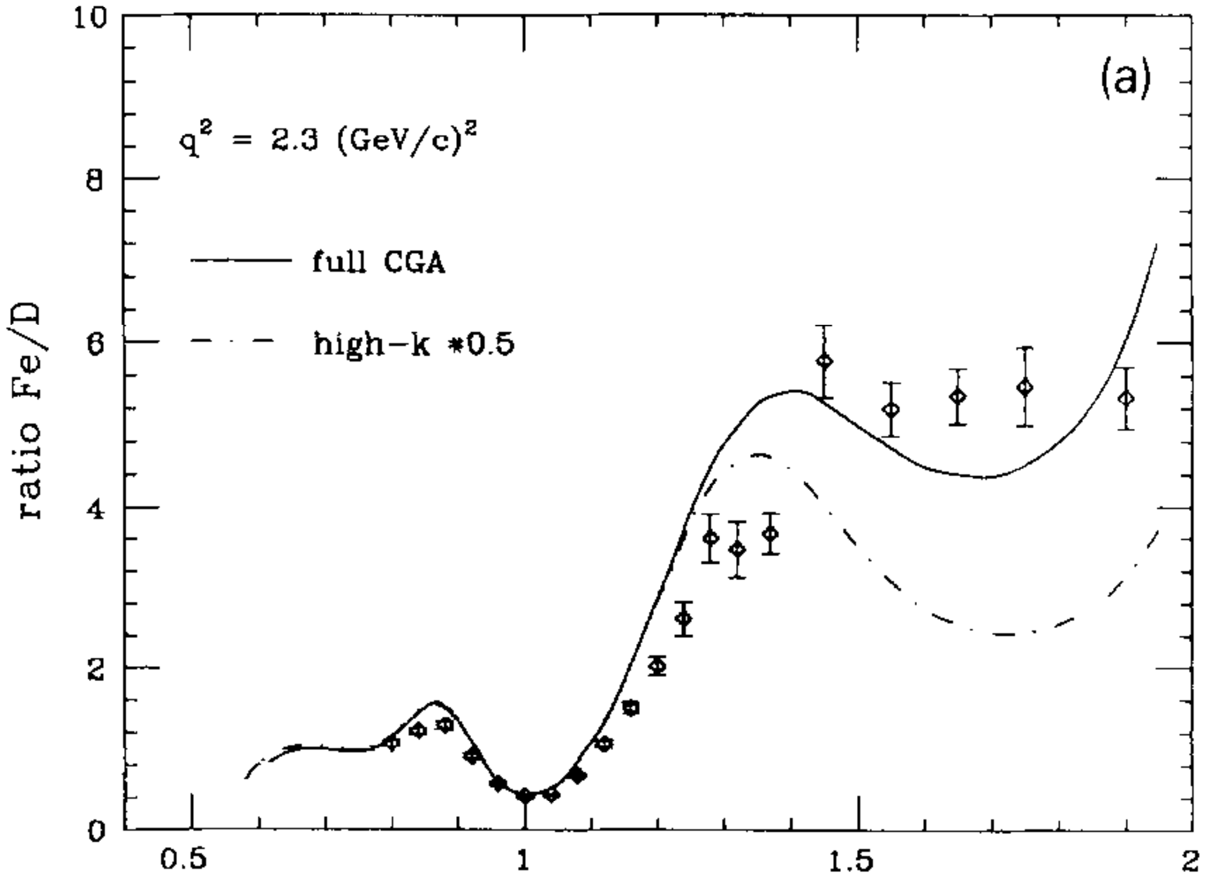
The plateaus, remarkable as they appear, are a result of FSI (and the role of SRC in FSI)

Ratios are NOT a measure of a_2 - the relative number of SRC pairs in nuclei



- The hand-waving argument that FSI effects might cancel in the A/d cross section ratios is contradicted by the quantitative calculations.
- The idea that the FSI could be the same as in the deuteron is also conceptually wrong: if the nuclear medium affects via Initial State Interaction the correlated 2-nucleon system --- it does as the high-k tail is (say) 4 times higher in a nucleus than in the deuteron --- then the nuclear medium also increases the FSI by a comparable factor.
- Indeed, in the standard Glauber-type calculations the FSI effects are explicitly proportional to the nuclear density.





At ω = 2000 MeV (y ≈ -0.50 and x = 1.75) FSI are not responsible for most of the strength.

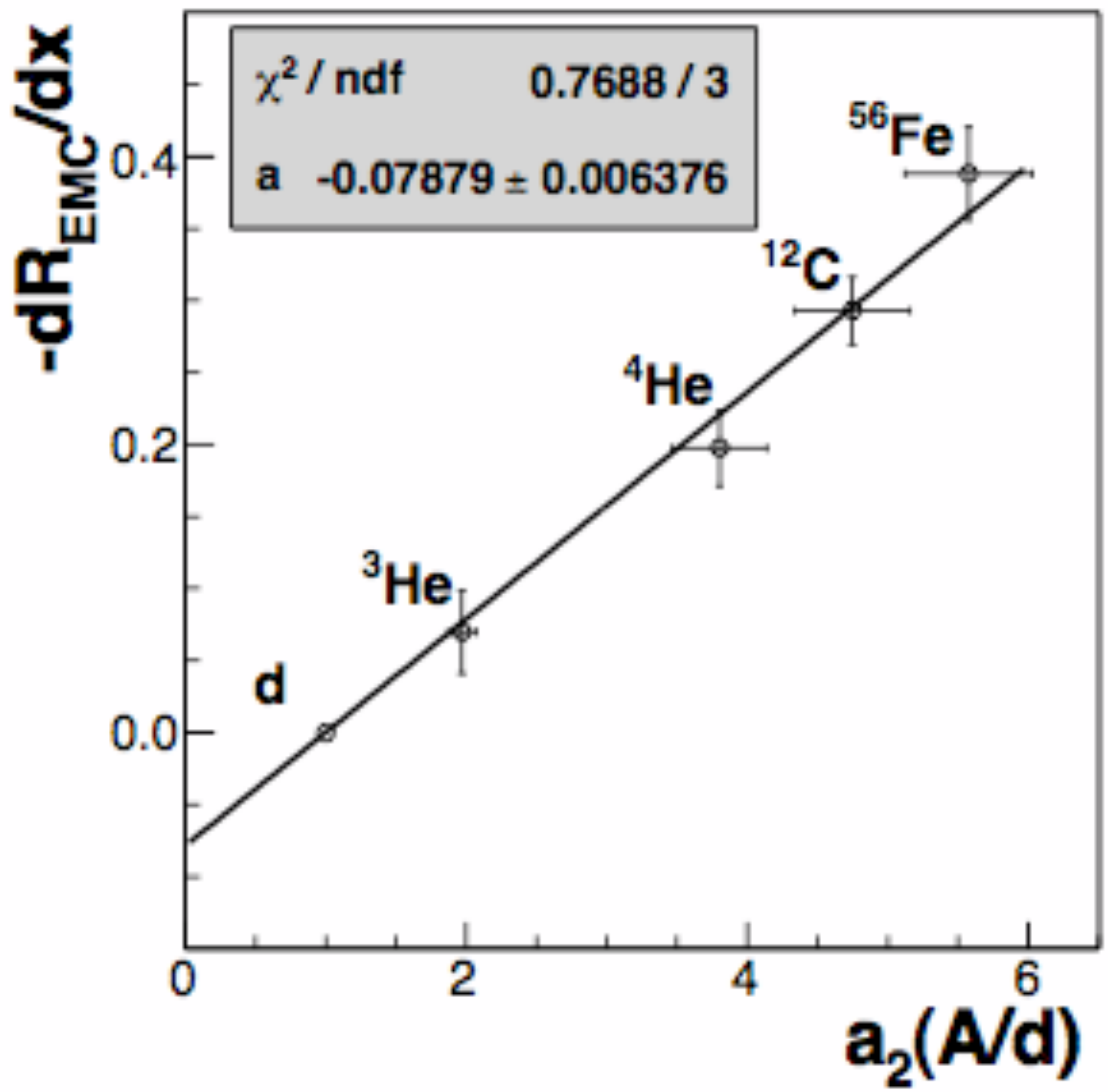
"Despite these complications the data at large x are sensitive to the properties of P(k,E) at large k…. The reduction of the high-k components by a factor of two, with the corresponding change of the short-range FSI has significant effect at x > 1.3."

Benhar et al, PLB 343 (1995) 47-52

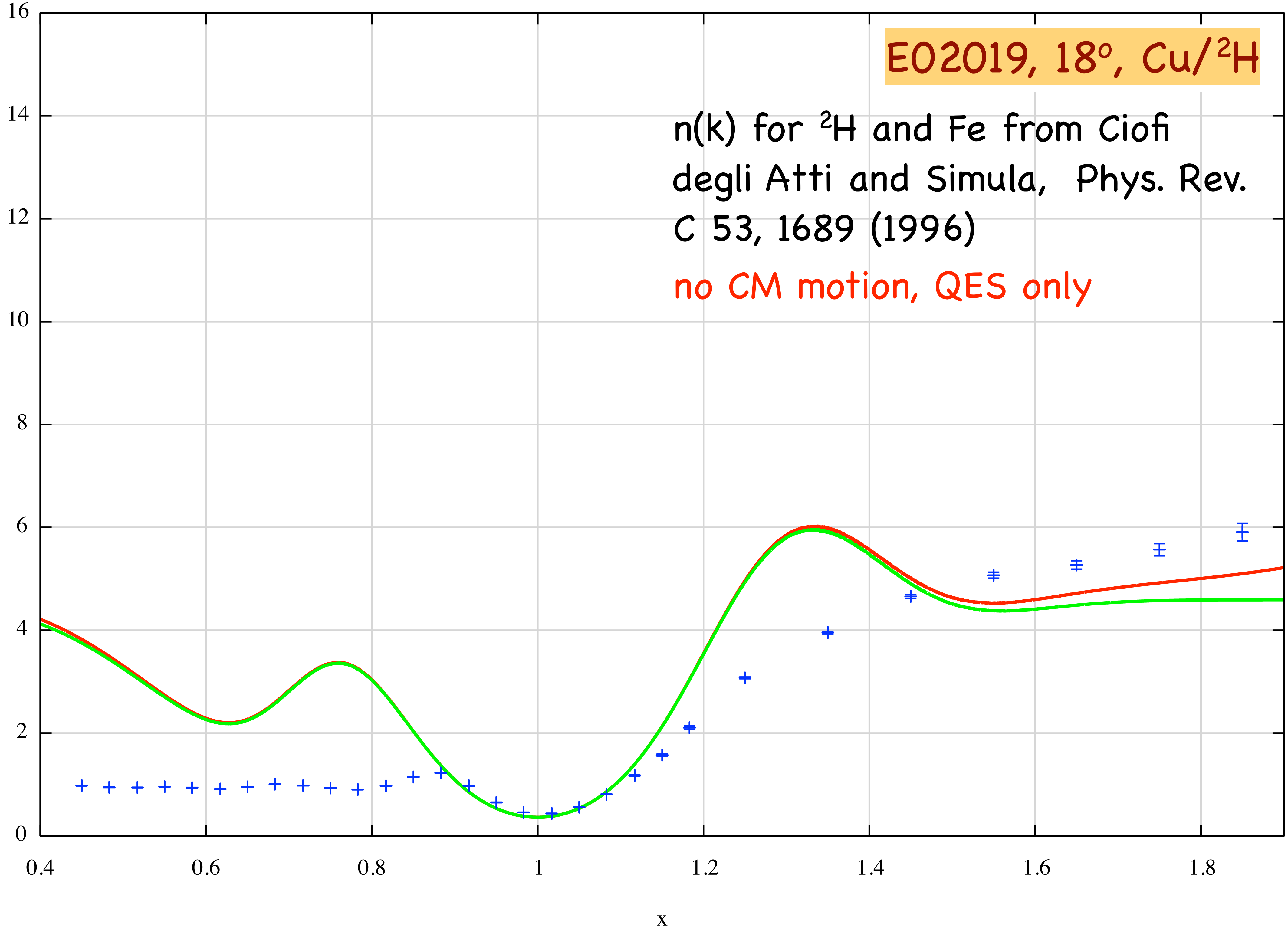
It would be useful to have new calculations that uses a spectral function that has the high k strength moved to match data.

If a_2 is an artifact or complicated from FSI then does it destroy this relation?

It can only survive if the FSI from ^{3}He to Au have a sympathetic relationship in the plateau region.



Ratios predictions from n(k)



What is an experimentalist to do?

Encourage theorists to examine FSI with respect to to the message the data is trying to send.

- 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

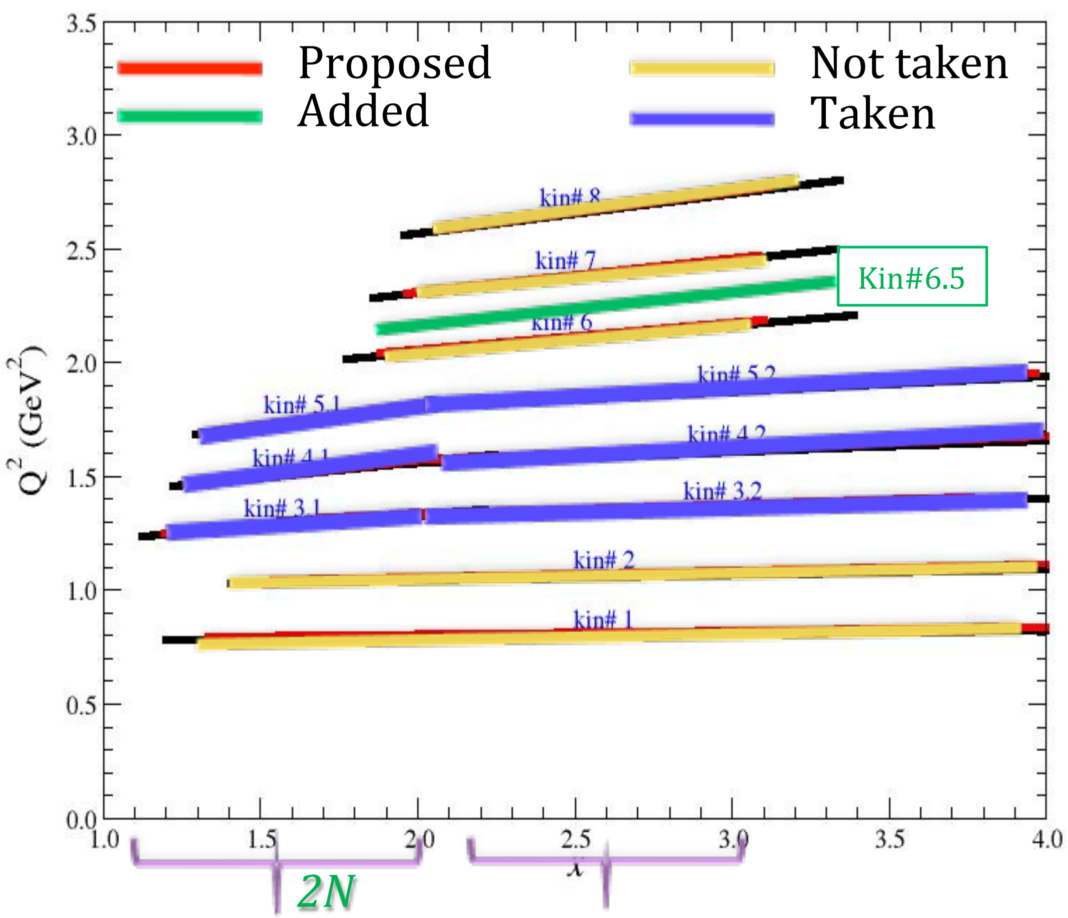
Experiments

- 6 GeV (completed in Spring 2011)
  - 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], approved.

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 $\rho_A()$
- Isospin effects on SRCs: ^{48}Ca vs. ^{40}Ca

Zhihong Ye, UVA graduate student



2N SRC

Kin 3.1: 21.0°, 2.905 GeV/c
^{2}He, ^{3}He, ^{4}He, ^{12}C, ^{40,48}Ca

Kin 4.1: 23.0°, 2.855 GeV/c
^{3}He, ^{12}C, ^{40,48}Ca

Kin 5.1: 25.0°, 2.795 GeV/c
^{2}H, ^{3}He, ^{4}He, ^{12}C, ^{40,48}Ca

3N SRC

Kin 3.2: 21.0°, 3.055 GeV/c
^{3}He, ^{4}He, ^{12}C, ^{40,48}Ca

Kin 4.2: 23.0°, 3.035 GeV/c
^{3}He, ^{4}He, ^{12}C, ^{40,48}Ca

Kin 5.2: 25.0°, 2.995 GeV/c
^{3}He, ^{4}He, ^{12}C, ^{40,48}Ca

Kin 6.5: 28.0°, 2.845 GeV/c
^{3}He, ^{12}C

Can we make an connection to 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

Poor resolution, limited x range

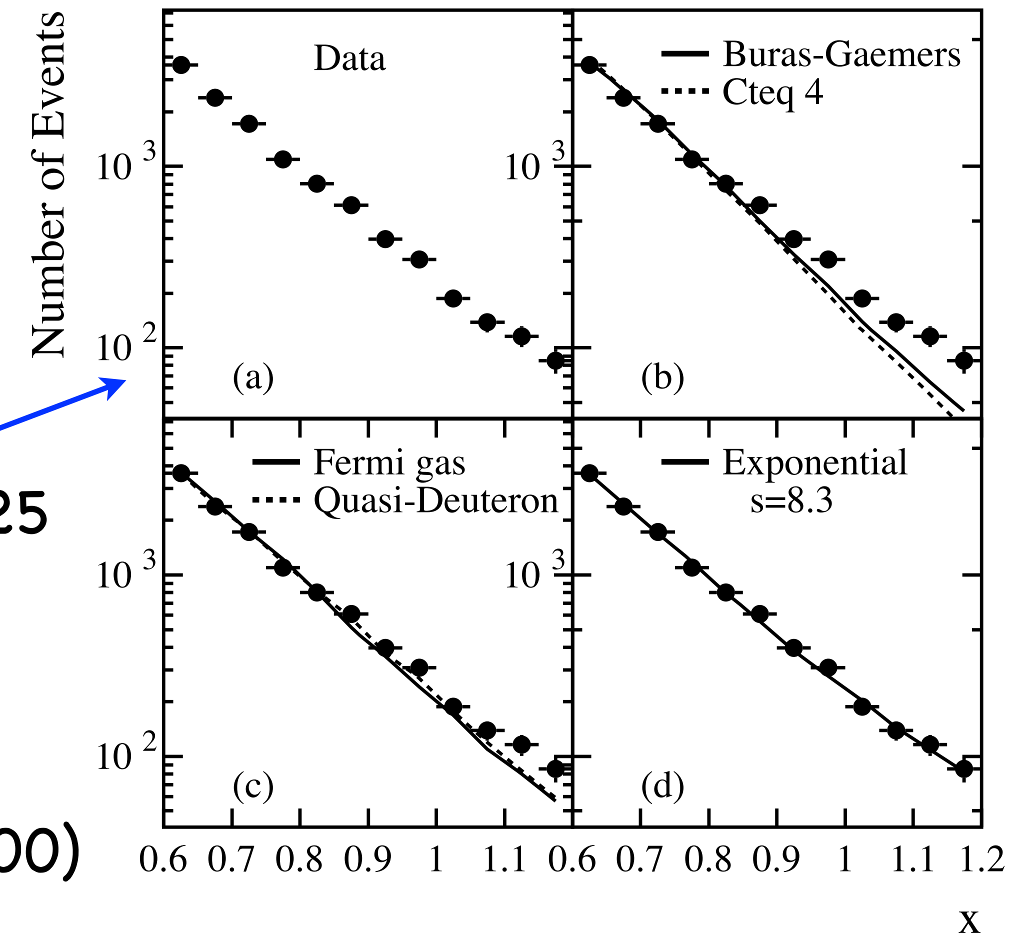
Low statistics

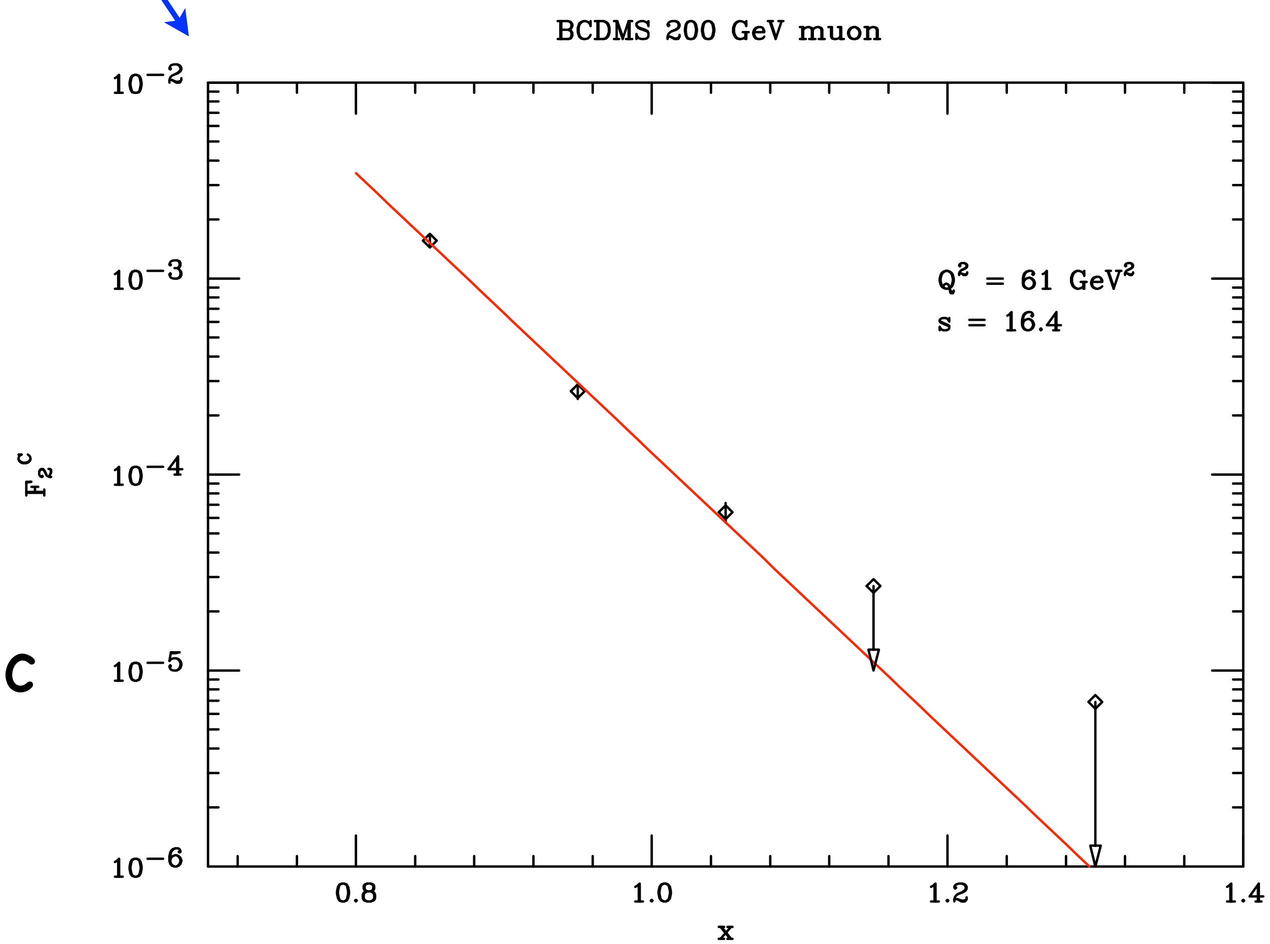
CCFR results suggested large contribution from SRC or other exotic effects

We can, but first we must account for the fact that none of these measurements are at the asymptotic limit.

125

60 (50-200)

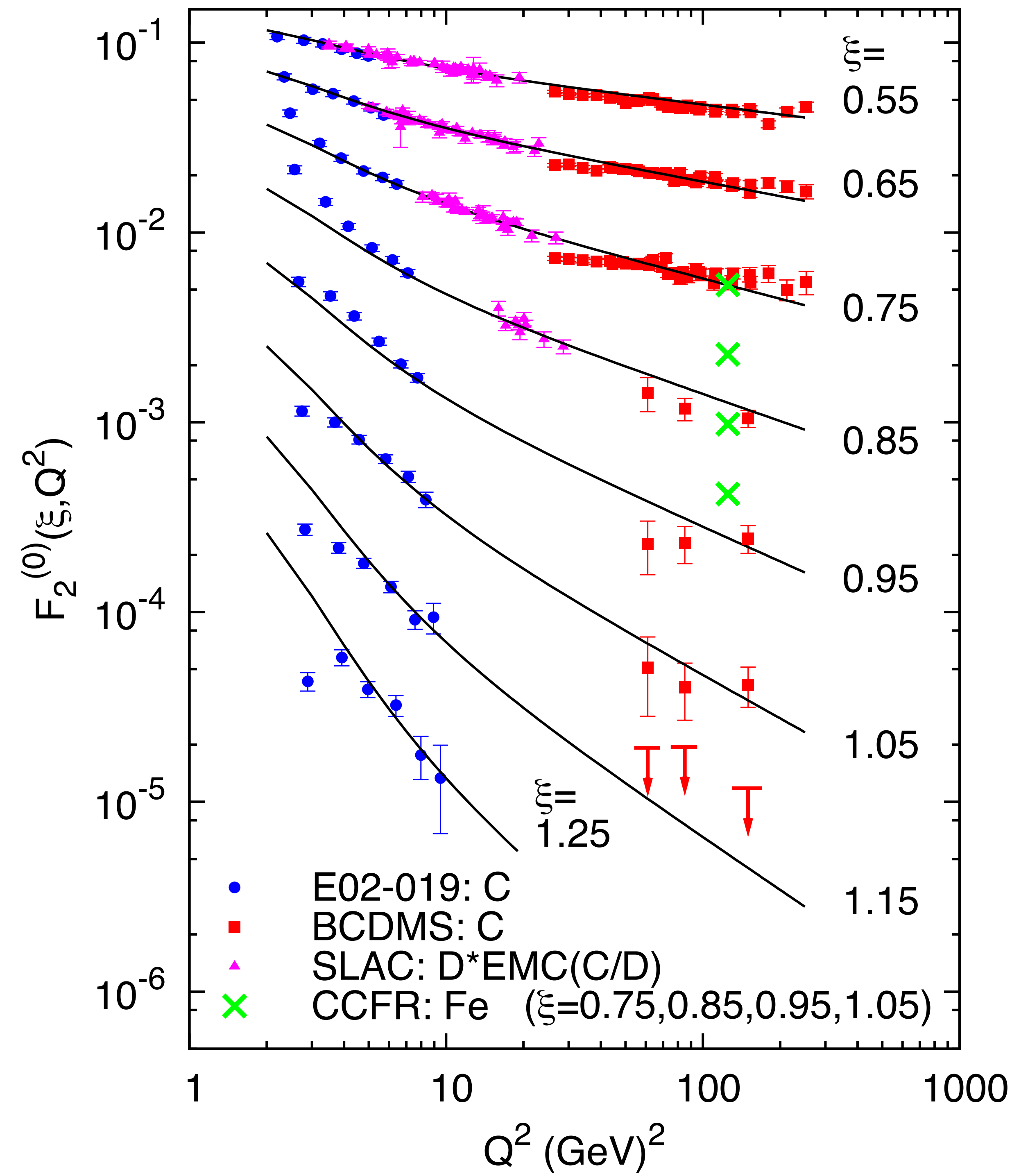




How well does this work?

The comparison to the world data set is good and can be used to extract the behavior of the SF at large x.

- At $\xi \leq 0.75$ where the high Q^2 data dominates our data the agreement is good down to about Q^2 = 3 GeV^2.
- As ξ increases the dependence on Q^2 grows continually.
- Agreement is still good except at low Q^2 where there is a QES contribution and HT must play a role
- Finally note that the BCDMS data fails to display a dependence on momentum transfer above ξ about 0.65

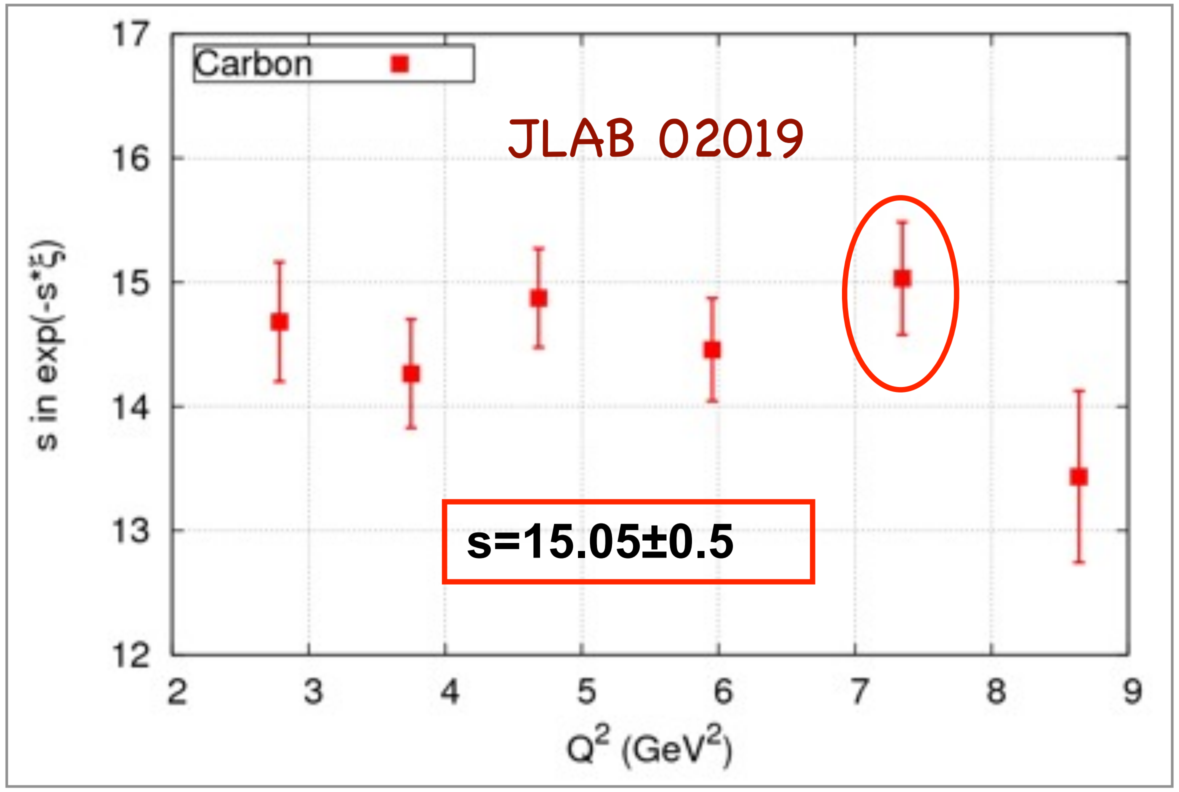


E02-019 carbon
SLAC deuterium
BCDMS carbon
× CCFR projection
(ξ=0.75,0.85,0.95,1.05)

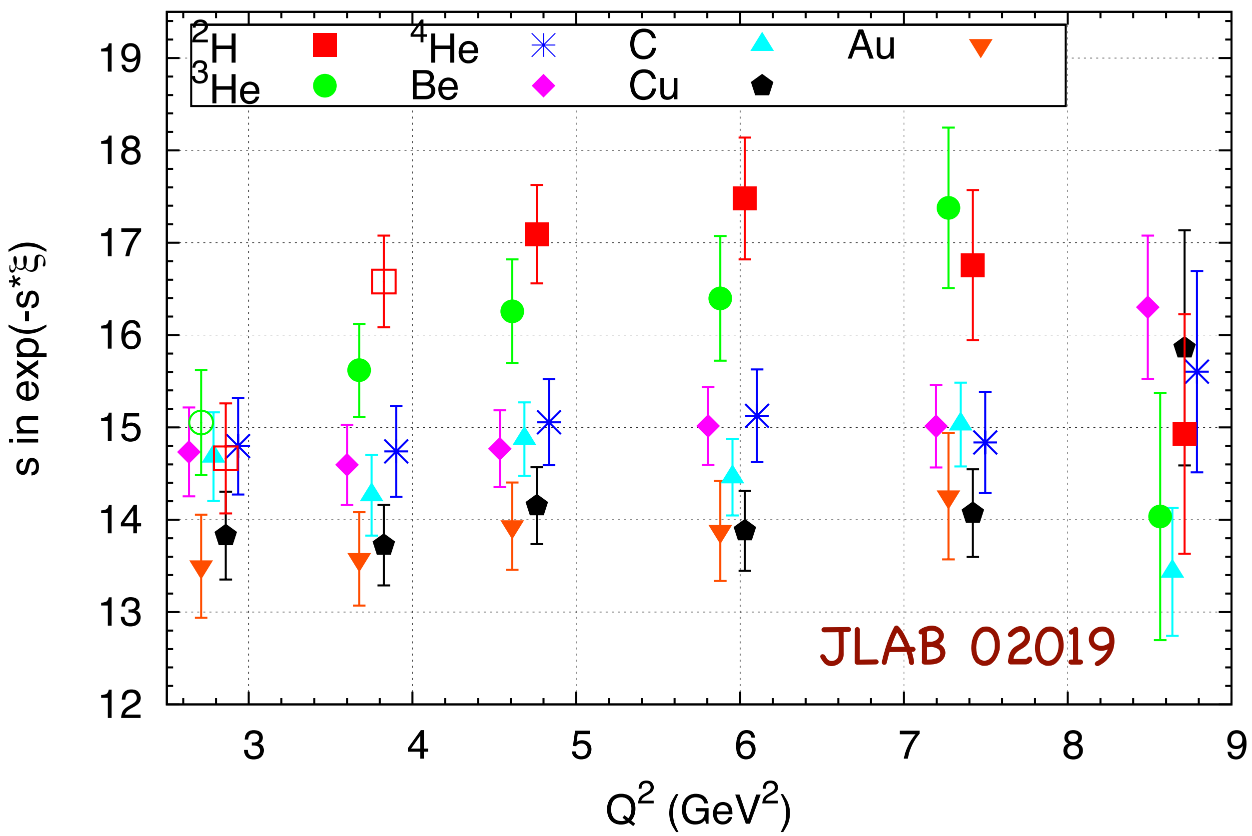
Compare to the very high Q^2 BCDMS and CCFR data

Fit our F_2^0 (over a limited range of ξ) with the functional form F_2^0 = Constant x $e^{(-s\xi)}$

CCFR – (Q^2 = 125 GeV^2)	s=8.3±0.7
BCDMS – (Q^2: 52 - 200 GeV^2)	s=16.5±0.5



For all nuclei

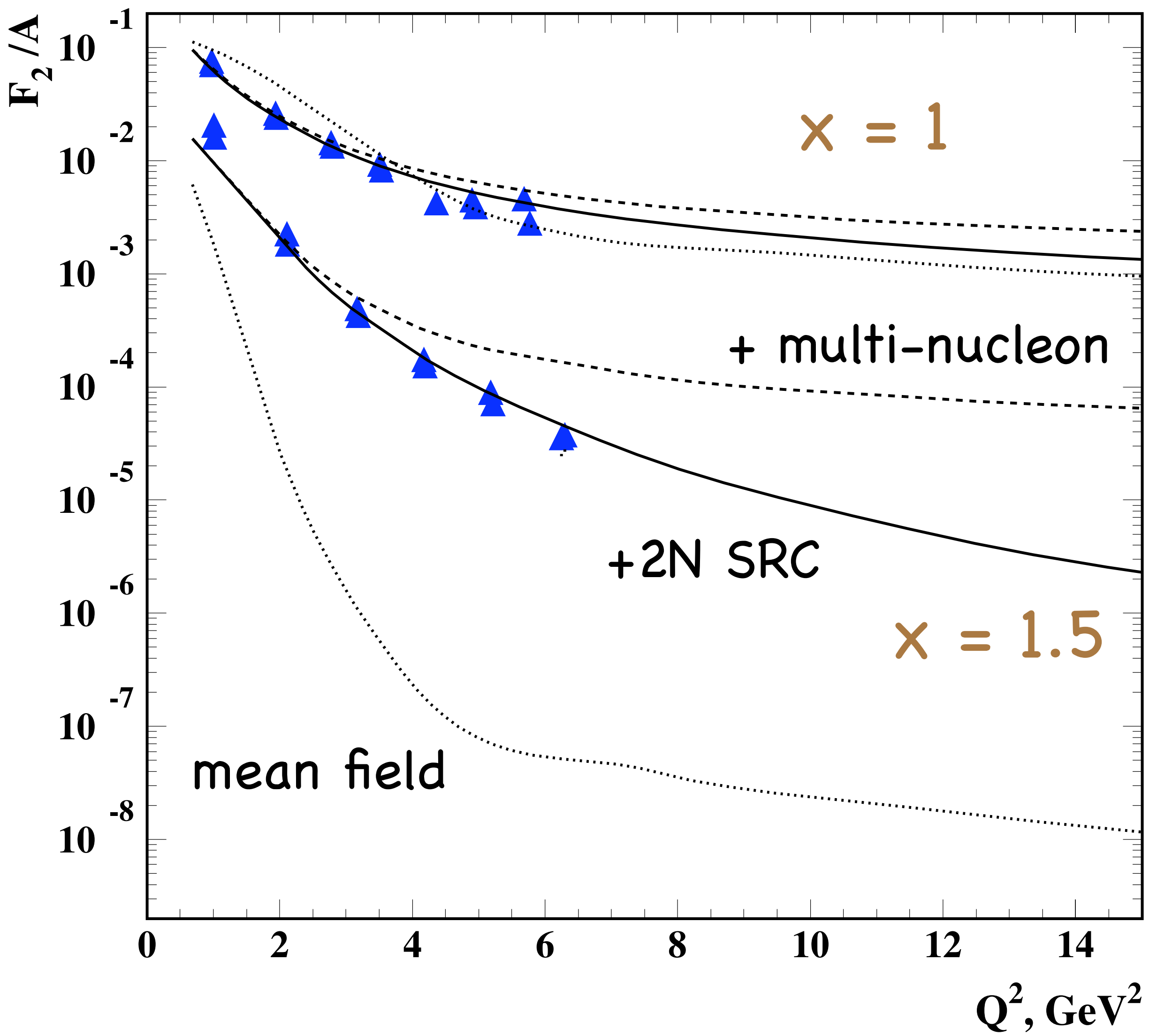


Our results contradict those of CCFR and support BCDMS

Sensitivity to SRC

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

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

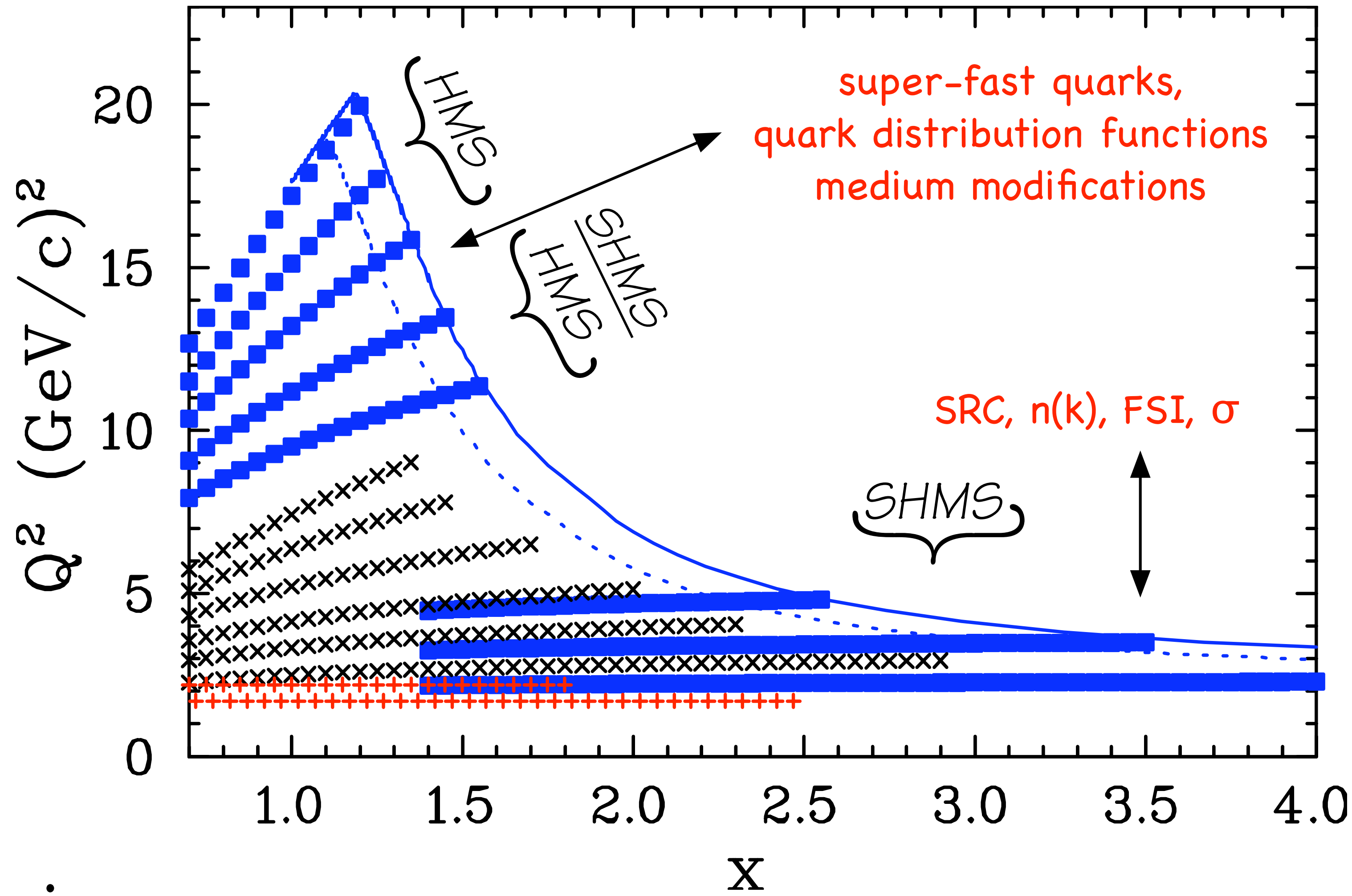


11 GeV can reach Q^2= 20(13) GeV^2 at x = 1.3(1.5)

- very sensitive, especially at higher x values

E12-06-105 Inclusive Scattering from Nuclei at x > 1 in the quasielastic and deeply inelastic regimes

^{2}H, ^{3}He, ^{4}He, $^{6,7}Li$, $^{10,11}Be$, ^{12}C, $^{40,48}Ca$, Cu, Au



Two distinct kinematic regimes

- Moderate Q^2 and large x
  - Two and multi-nucleon correlations
    - A-dependence of strength, density dependence, non-isoscalarity
  - Provide tests of 'exact' calculations [S(k,E)] through σ, expose role of FSI
- Very high Q^2 and $1 < x < 1.5$
  - Extraction of SF and underlying quark distributions at x > 1
  - Provide insight into origin of EMC effect
  - Provide extreme sensitivity to non-hadronic components

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
- New experiments have been approved to push these investigations into heretofore unexplored regions

If it was only this easy.

The correlation between the FTSE and the DOW for the last 6 months.