Electromagnetic Nuclear Interactions at GeV Energies

Can electron scattering data contribute to an understanding of the backgrounds?

Donal Day
University of Virginia

Cosmogenic Activity and Backgrounds

April 13 - April 15, 2011

Berkeley

Formaggio and Martoff ARNPS (2004)

"Cosmic ray muons produce neutrons through several different mechanisms..."

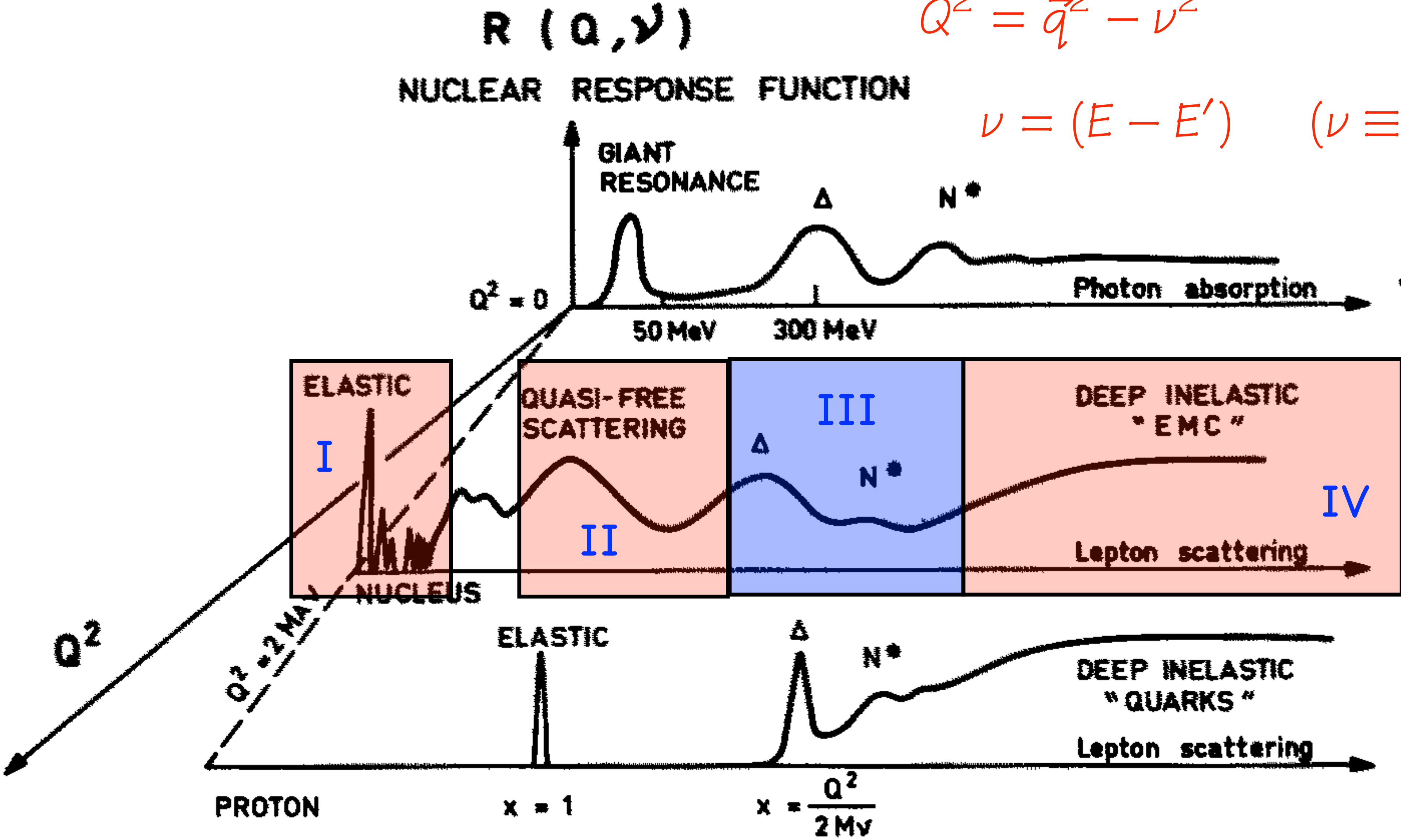
1. Negative muon capture on nuclei.
2. Electromagnetic showers generated by muons.
3. Muon interactions with nuclei via the exchange of virtual photons ==> muon nuclear interactions and photoneutron production.
4. Muon-nucleon quasielastic scattering.

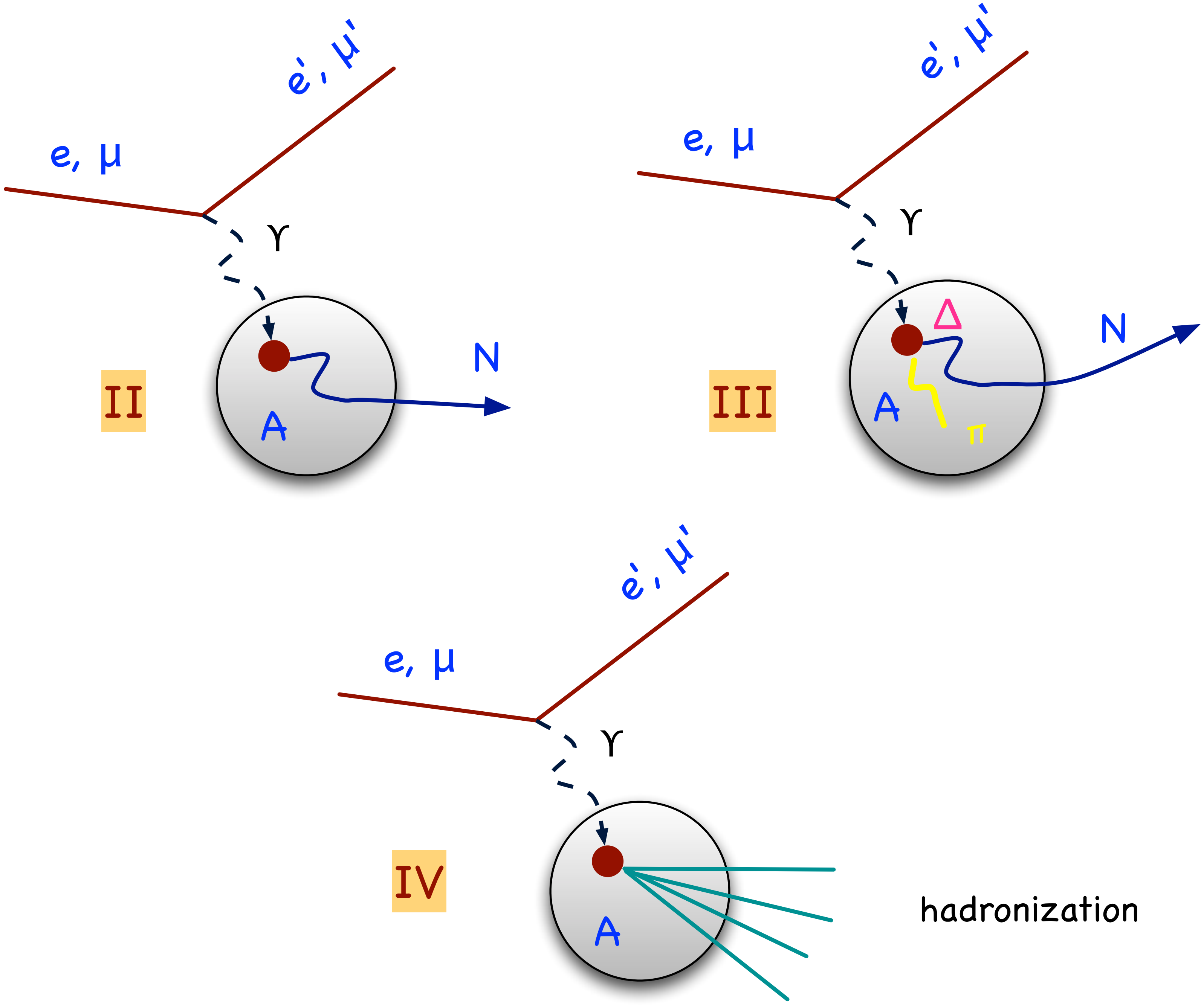
These energetic neutrons (100's of MeV) are produced thru quasielastic and inelastic processes from moving nucleons in the nucleus

Nuclear Response Function

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

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





What studies motivate inclusive inelastic electron scattering from nuclei?

A variety of topics

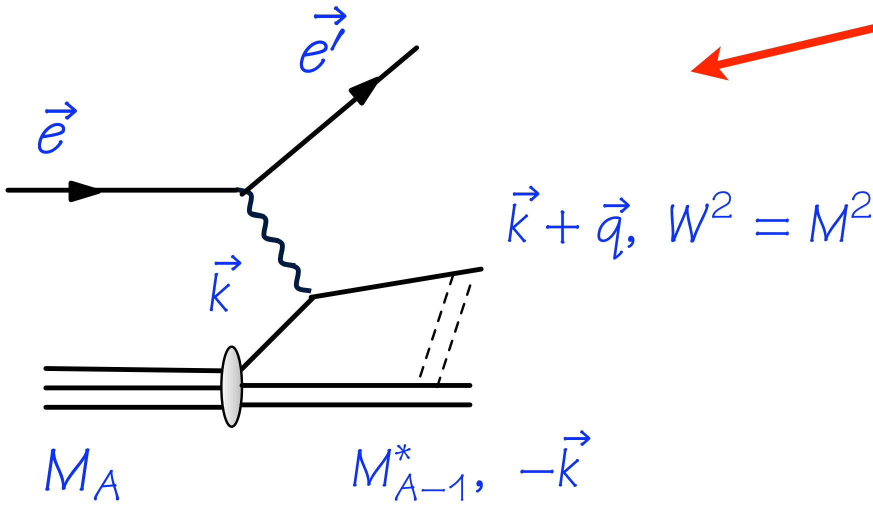
- Momentum distributions and the spectral function S(k,E).
- Short Range Correlations and Multi-Nucleon Correlations
- Scaling (x, y, φ′, ξ) - tests and the violation of 'laws'
- Medium Modifications -- effects of the nuclear environment (EMC, exotic quark states)
- Duality - The strongly Q^2 dependent resonance structure function averages to DIS scaling - access to pdfs at very high x

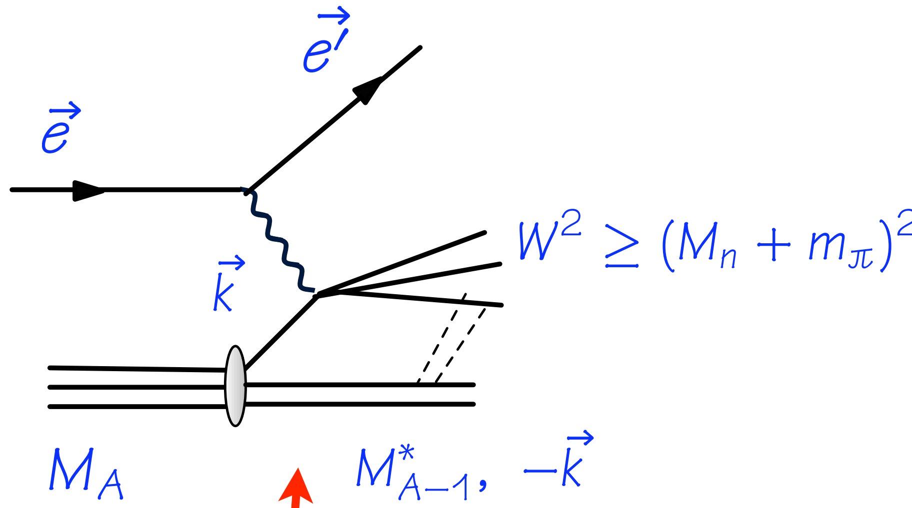
The inclusive nature of these studies make disentangling all the different pieces a challenge but we have a couple of knobs....

Inclusive Electron Scattering from Nuclei

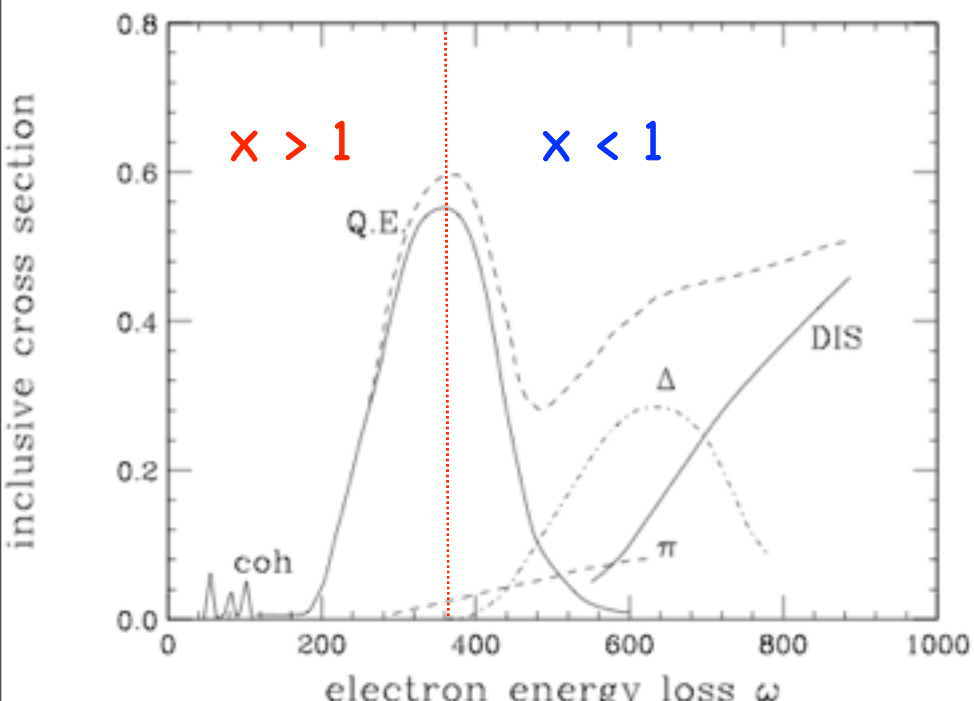
Two distinct processes

Quasielastic from the nucleons in the nucleus





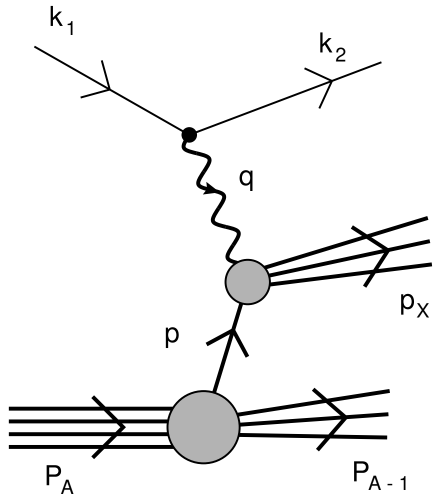
Inelastic (resonance production) and DIS from the quark constituents of the nucleon.



Inclusive final state means no separation of two dominant processes

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

υ,ω=energy loss



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

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

The two processes share the same initial state

QES in IA

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

DIS

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

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

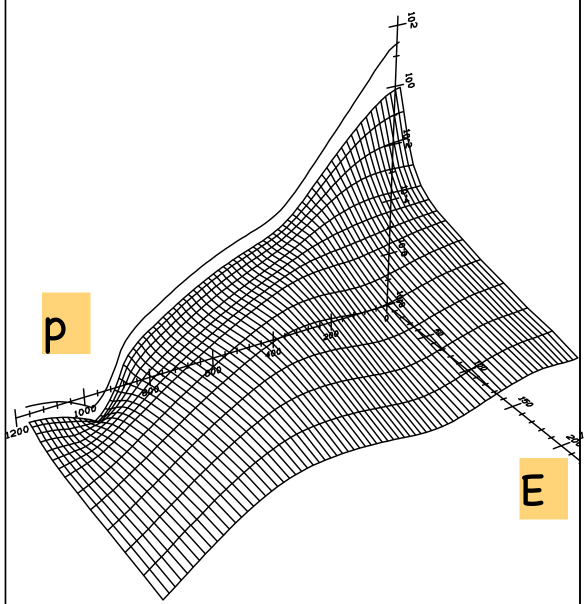
However they have very different Q^2 dependencies

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

Exploit this dissimilar Q^2 dependence

Spectral Function

Helium - 3



Faddeev, Hanover group

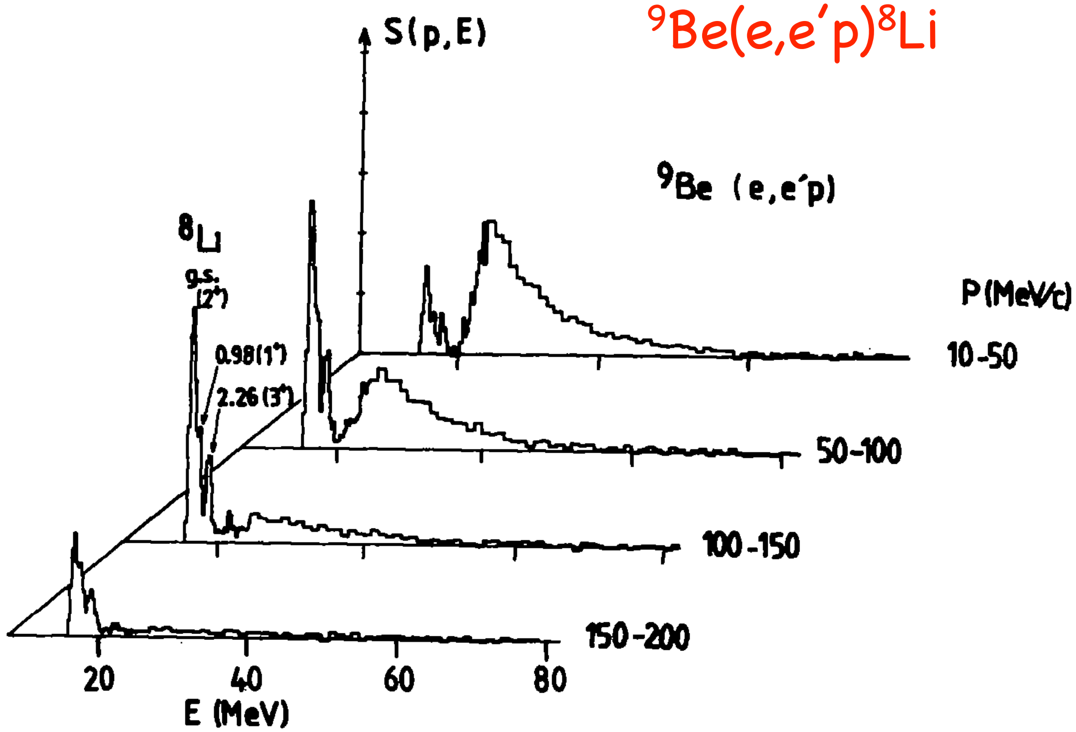
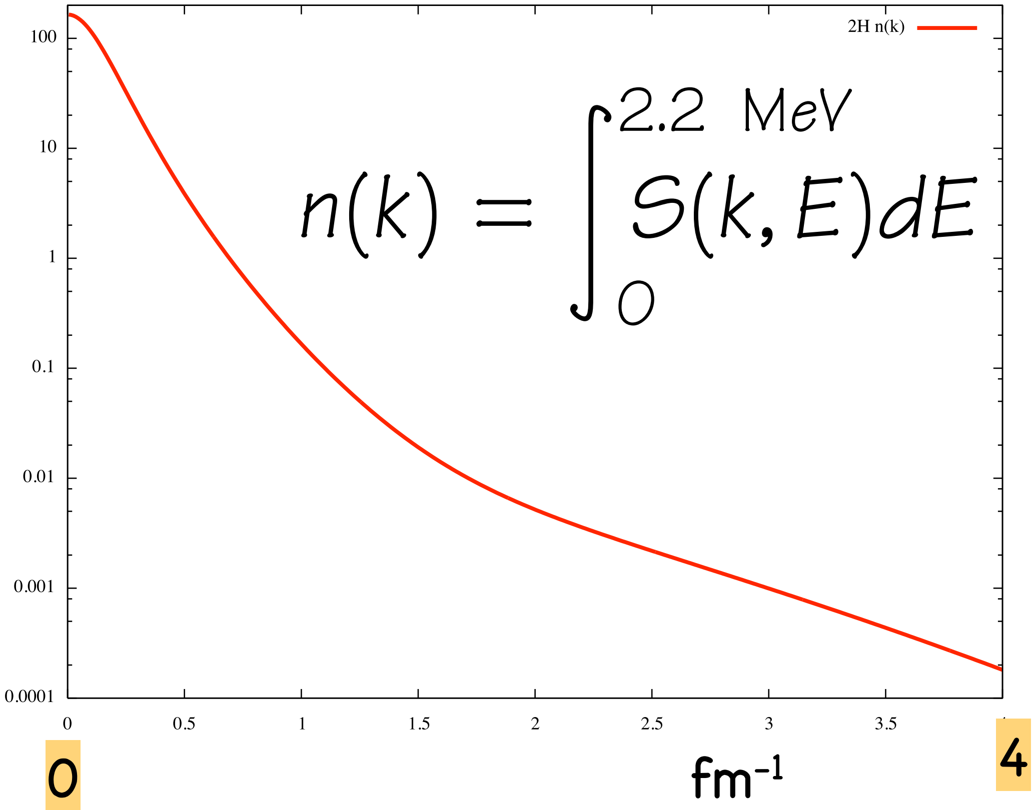


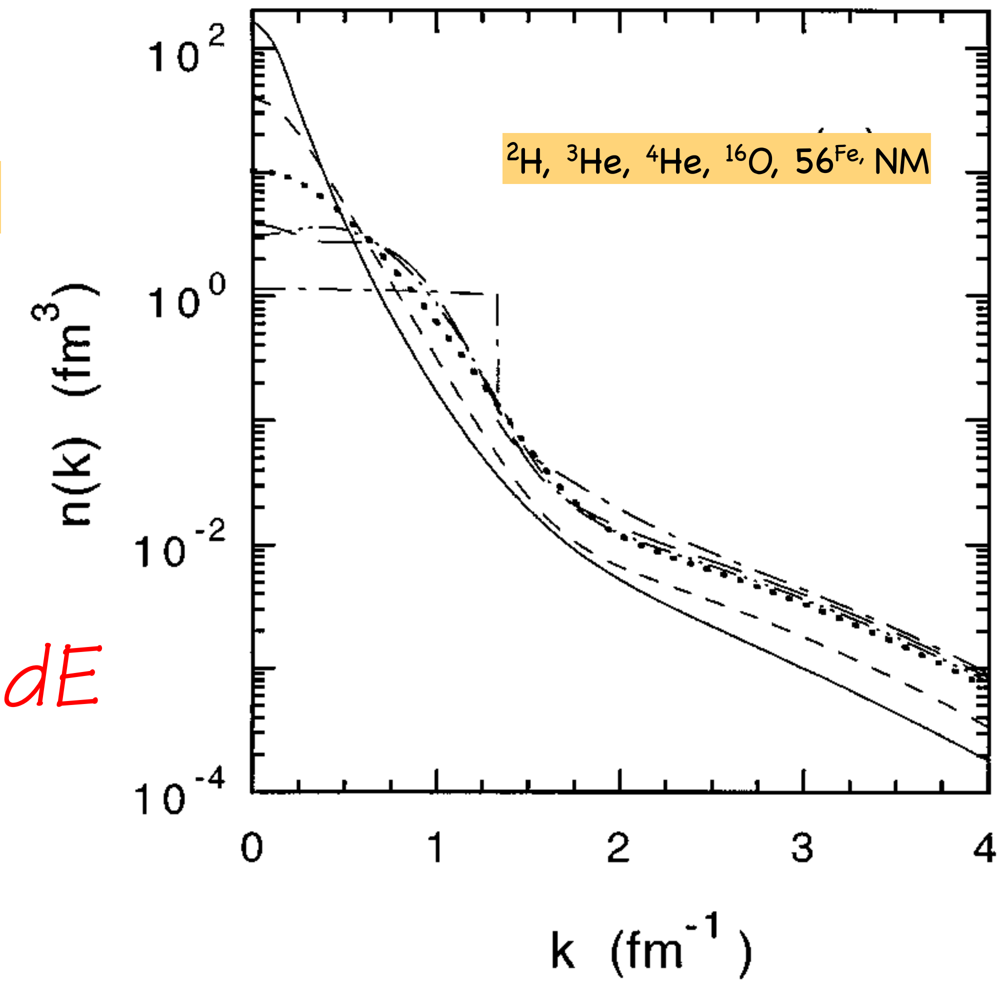
Fig. 10. Proton separation energy spectra for the ^{9}Be(e,e'p) reaction, within different recoil momentum bins. The energy resolution of ∼ 0.9 MeV renders visible some different excited states of ^{8}Li at low separation energy. Data have been corrected for radiative effects, but the overall absolute scale is arbitrary.

Saclay, J. Mougey



$$n(k) = \int_0^{2.2\ \mathrm{MeV}} S(k,E)dE$$

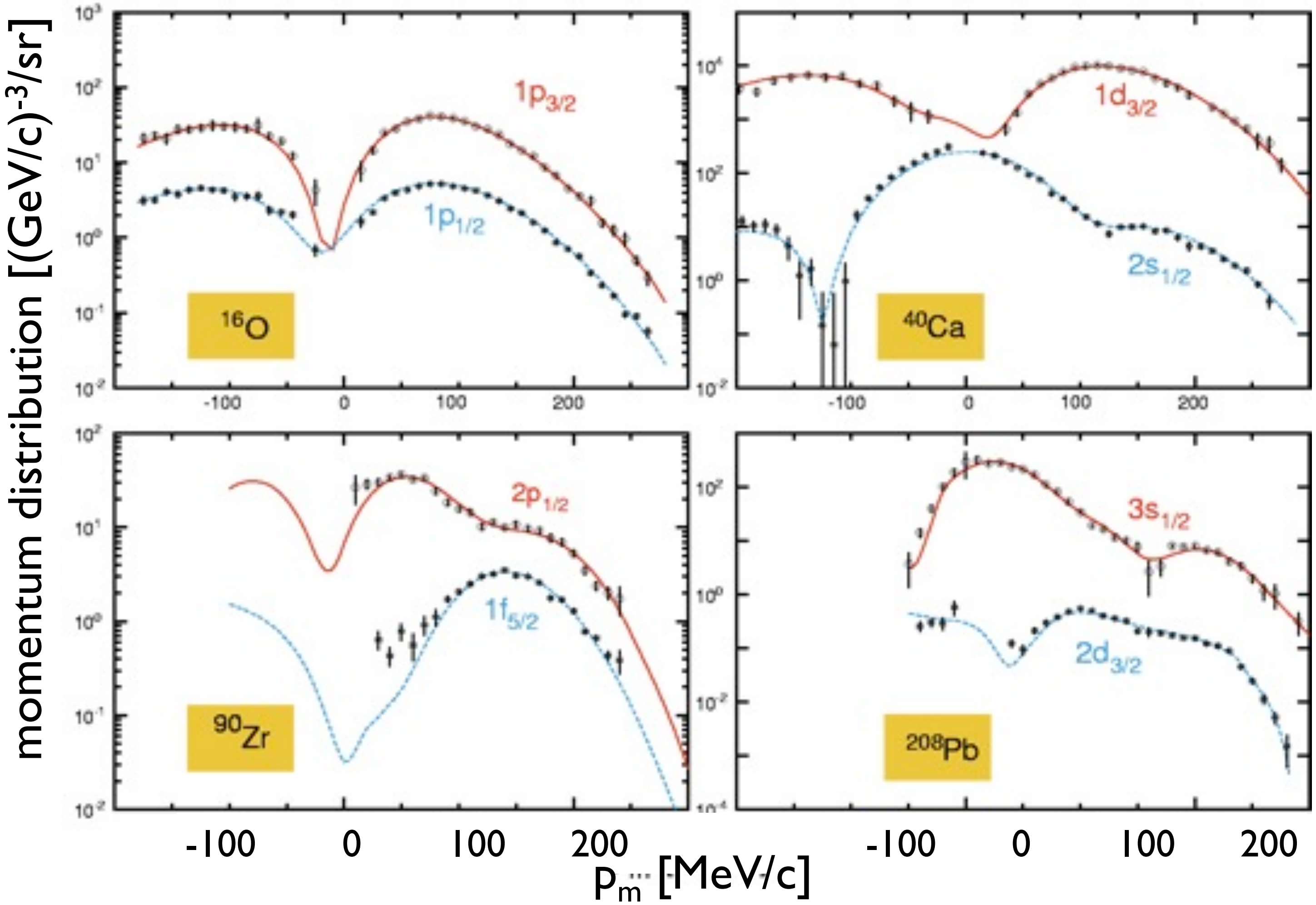
Momentum distribution is integral of spectral function over the separation energy



$$n(k) = \int_0^{\infty} S(k,E)dE$$

Independent Particle Shell model: describes basic properties like

spin, parity, magic numbers ...



NIKHEF results

But there is a problem!

Spectroscopic factor $Z_\alpha = 4\pi \int^{k_f} dE\, dk\, k^2 S(k, E)$ ≠ number of nucleons in shell

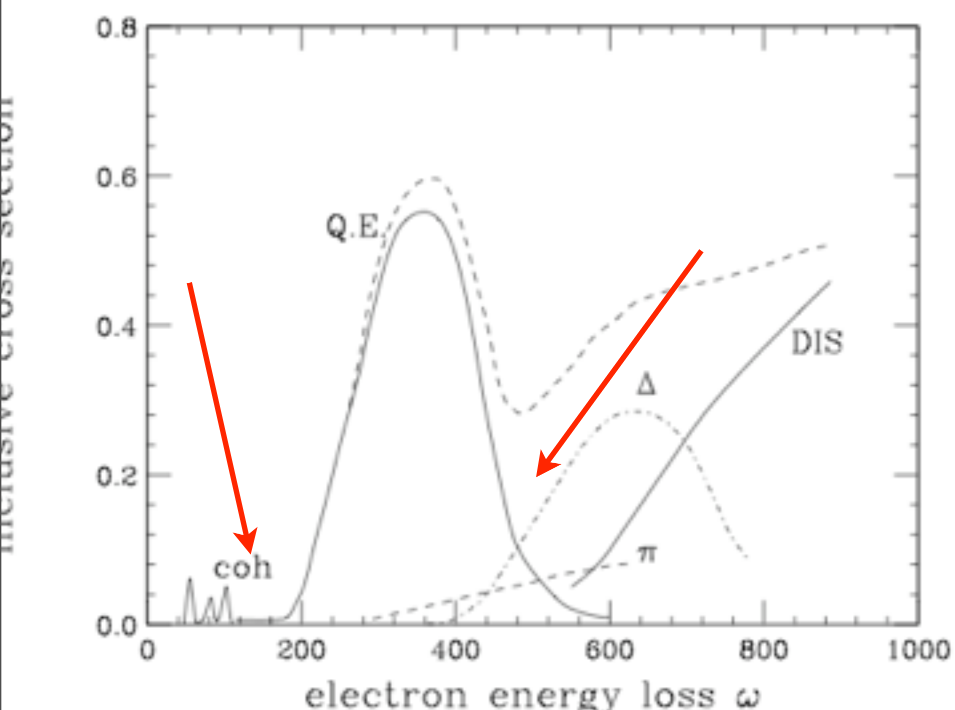
single particle state α

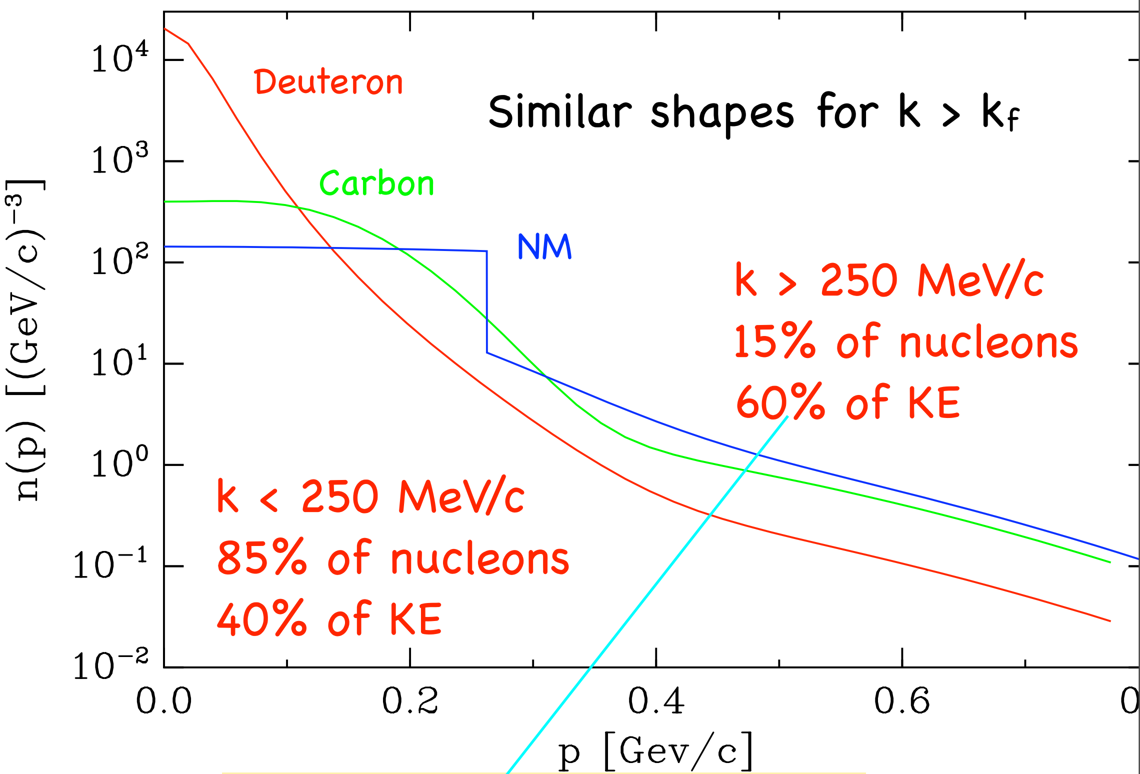
Short Range Correlations (SRCs)

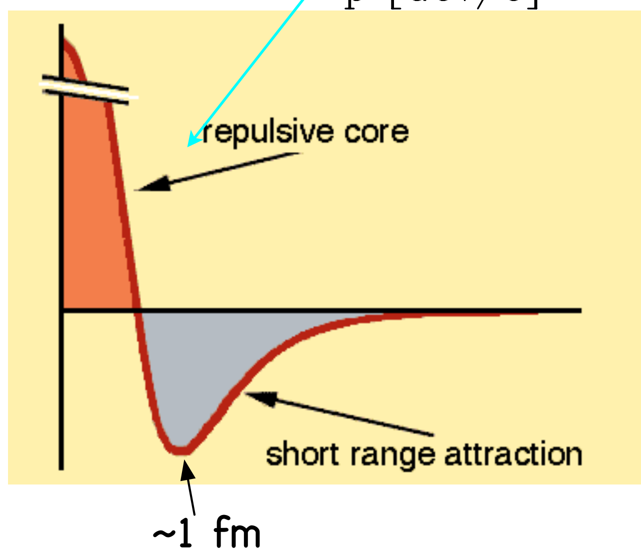
Mean field contributions: $k < k_F$ Well understood, SF Factors ≈ 0.65

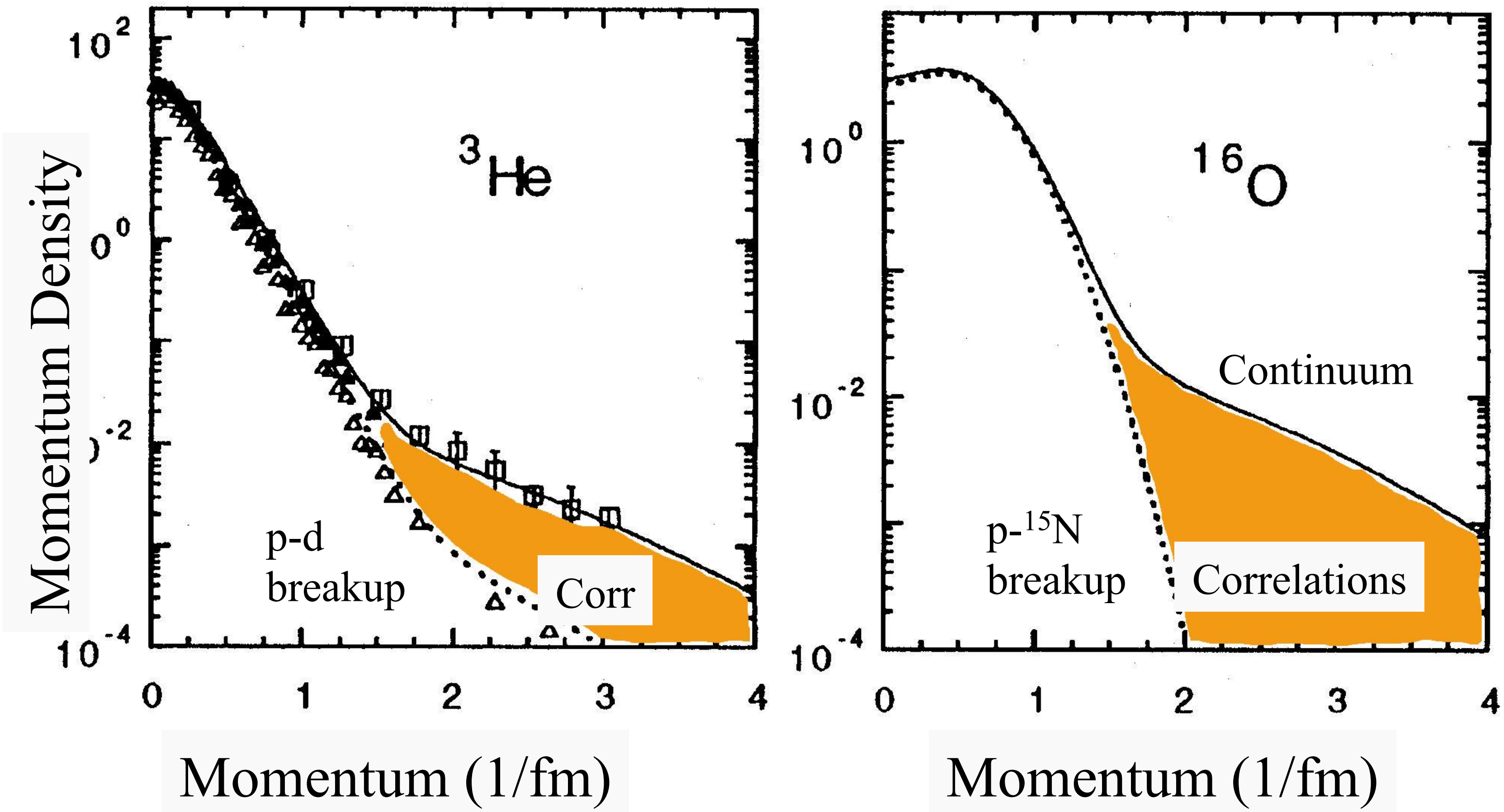
High momentum tails: $k > k_F$

- Calculable for few-body nuclei, nuclear matter
- Dominated by two-nucleon short range correlations
- Poorly understood part of nuclear structure
- Sign. fraction have $k > k_F$







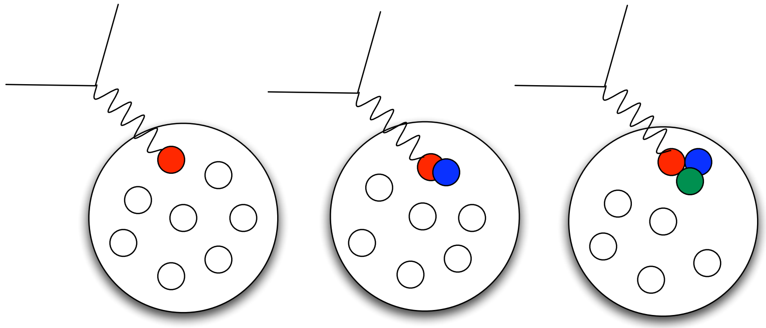


Ciofi degli Atti, PRC 53 (1996) 1689

This strength must be accounted for when trying to predict the cross sections

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.

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

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

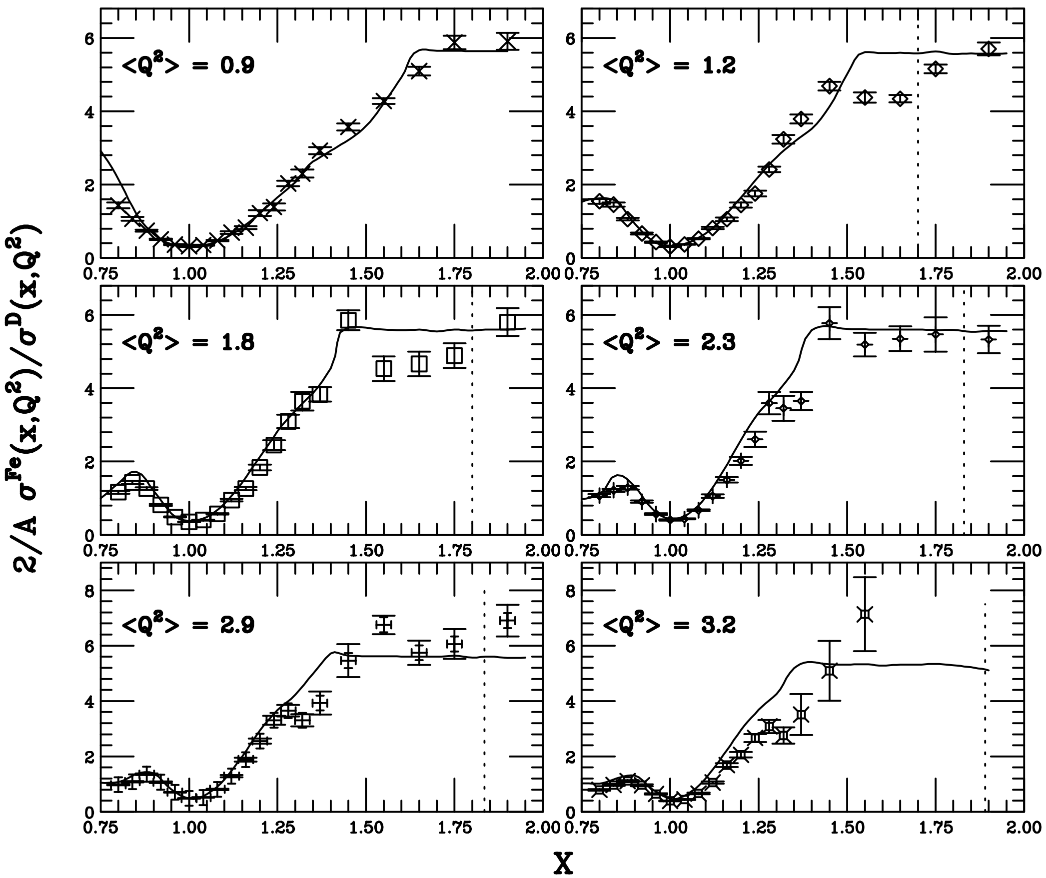
$$\frac{3}{A}\frac{\sigma_A(x,Q^2)}{\sigma_{A=3}(x,Q^2)} = a_3(A)\Big|_{2<x\leq 3}$$

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

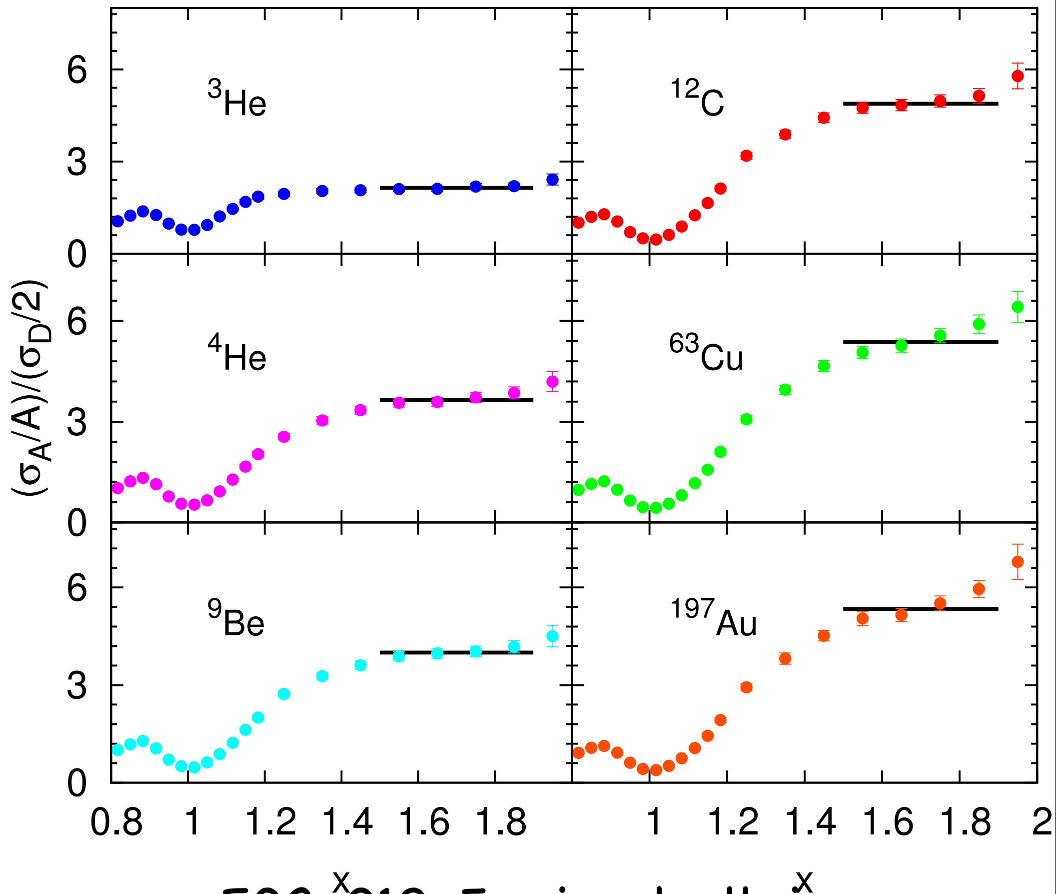
$a_j(A)$ is proportional to probability of finding a j-nucleon correlation

Ratios and SRC

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



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



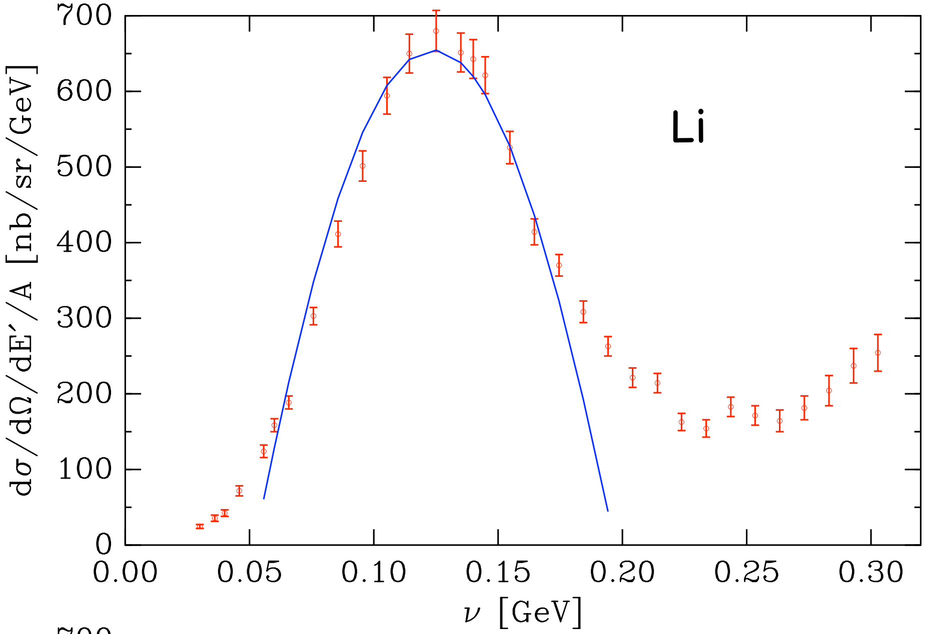
E02-019, Fomin at all, in prep

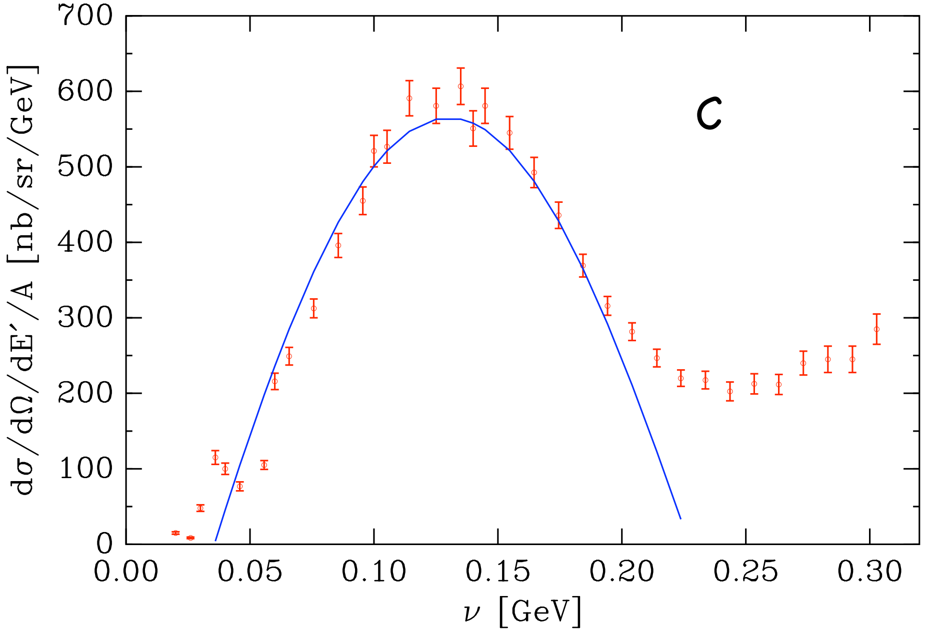
$a_j(A)$ is proportional to probability of finding a j-nucleon correlation

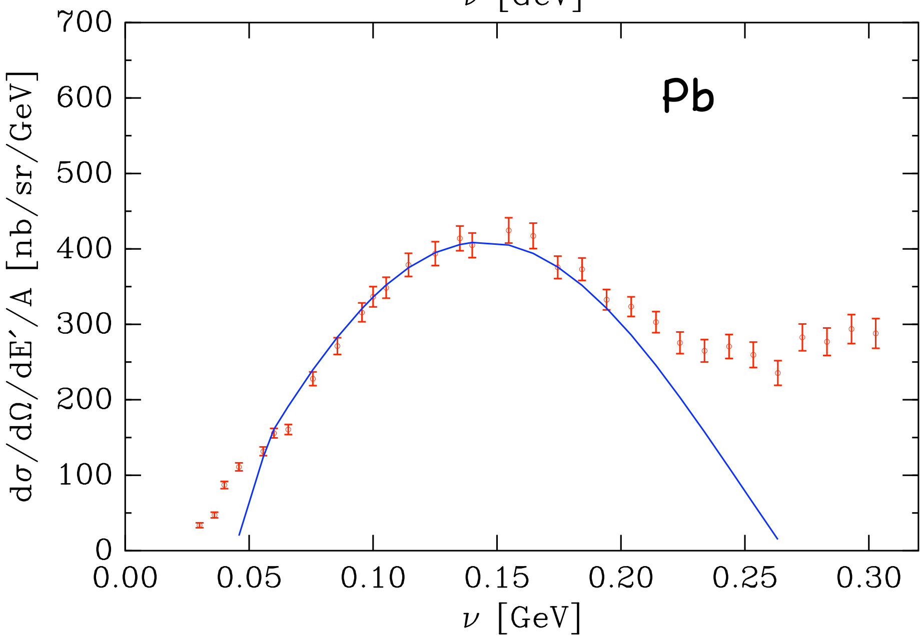
Early 1970's Quasielastic Data

500 MeV, 60 degrees

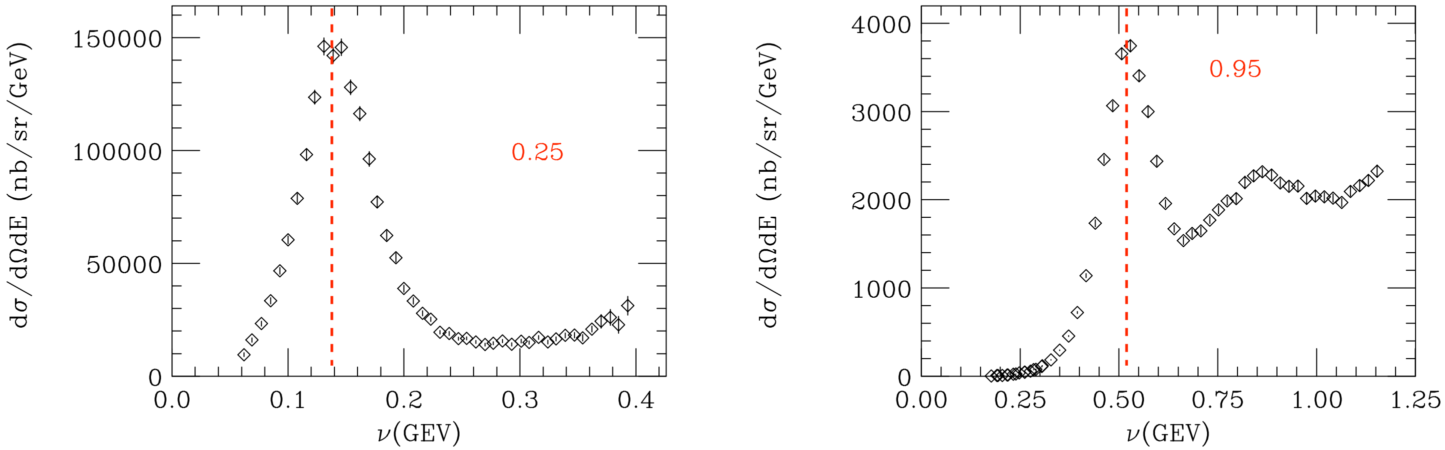
$\vec{q} \simeq 500 MeV/c$



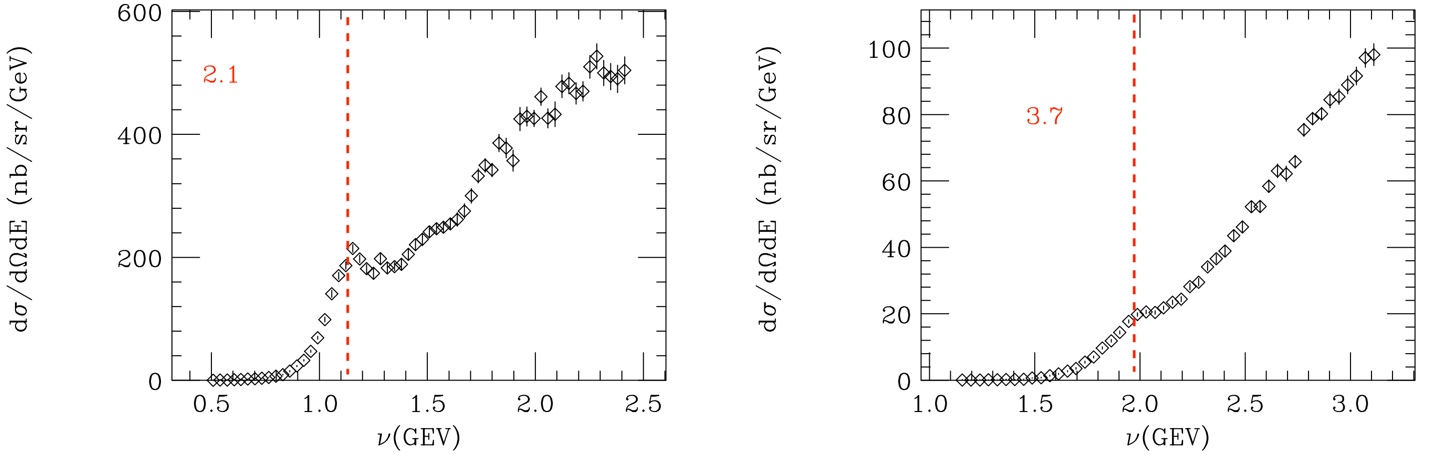




Nucleus	k_F	$\bar{\epsilon}$
^{6}Li	169	17
^{12}C	221	25
^{24}Mg	235	32
^{40}Ca	251	28
^{nat}Ni	260	36
^{89}Y	254	39
^{nat}Sn	260	42
^{181}Ta	265	42
^{208}Pb	265	44



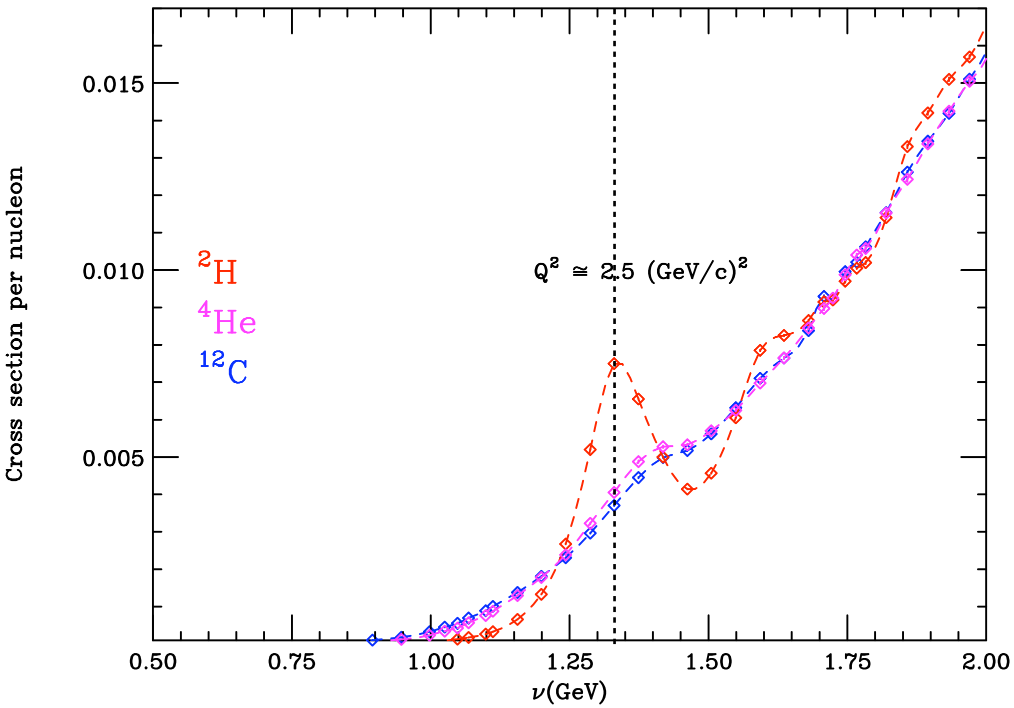
^{3}He SLAC (1979)

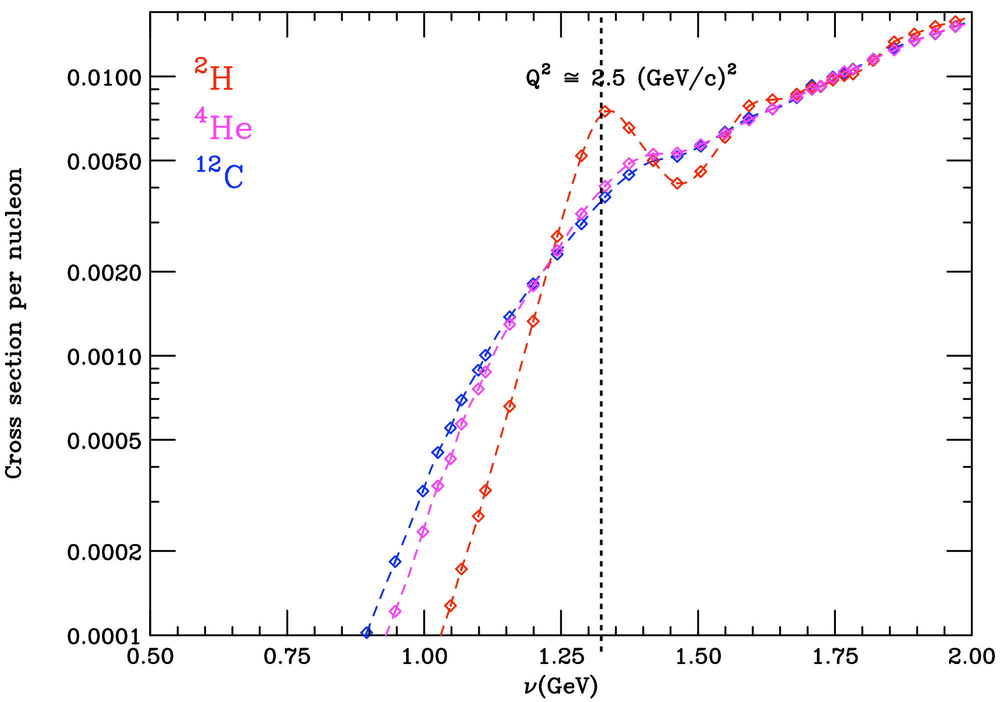


The quasielastic contribution dominates the cross section at low energy loss (ν) even at moderate to high Q^2.

- 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





Also note while broadening the qep it also sweeps strength from the inelastic regions

Scaling

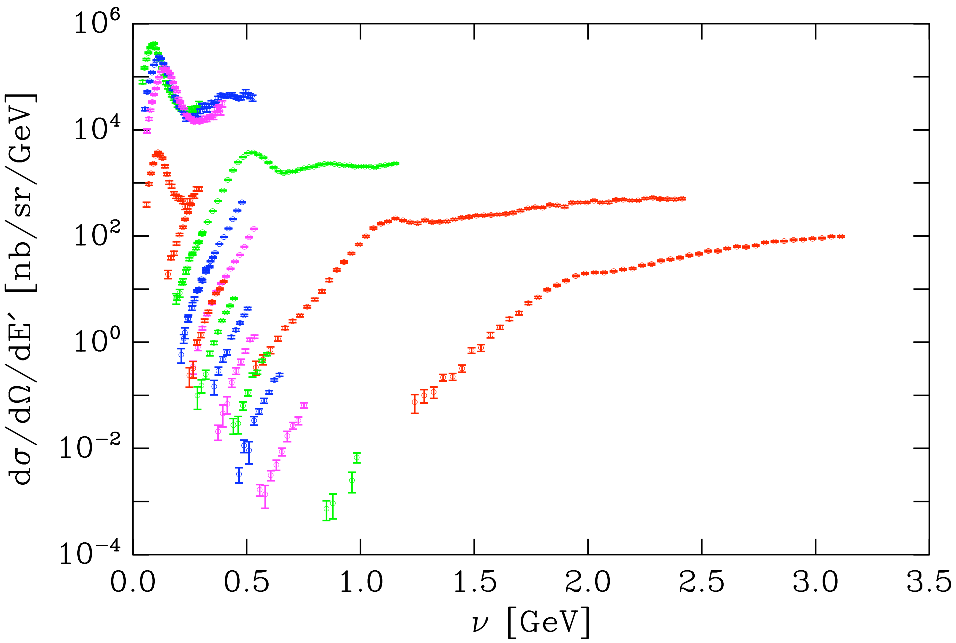
- Scaling refers to the dependence of a cross section, in certain kinematic regions, on a single variable.
  - Scaling validates the assumptions about the underlying physics
  - Scale-breaking provides information about conditions that go beyond the assumptions.

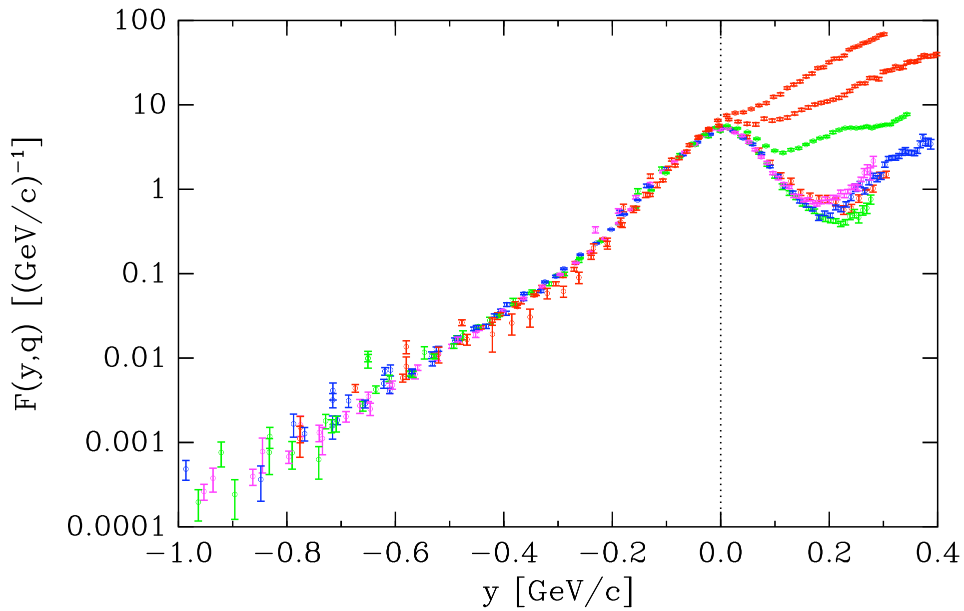
- At moderate Q^2 inclusive data from nuclei has been well described in terms y-scaling, one that arises from the assumption that the electron scatters from quasi-free nucleons.

- We expect that as Q^2 increases we should see for evidence (x-scaling) which could be interpreted as scattering from the more fundamental constituents - quarks.

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

y = 0 at quasielastic peak





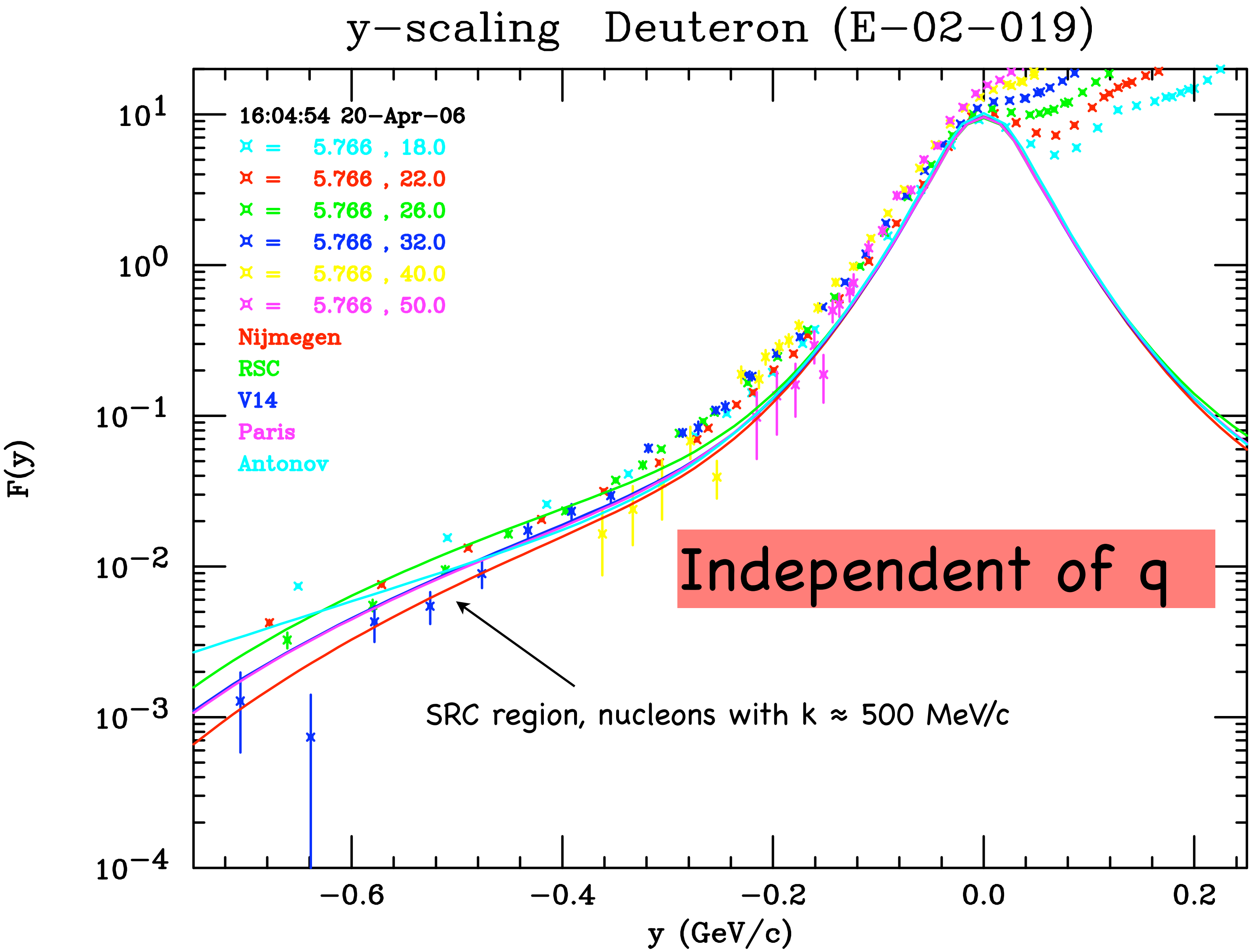
$$F(y) = \frac{\sigma^{\text{exp}}}{(Z\tilde{\sigma}_p + N\tilde{\sigma}_n)} \cdot K$$

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

Assumption: scattering takes place from a quasi-free proton or neutron in the nucleus. y is the momentum of the struck nucleon parallel to the momentum transfer:

$$y = y(q,\omega) \simeq \sqrt{\omega(2m_n + \omega)} - q$$

Deuteron F(y) and calculations based on NN potentials



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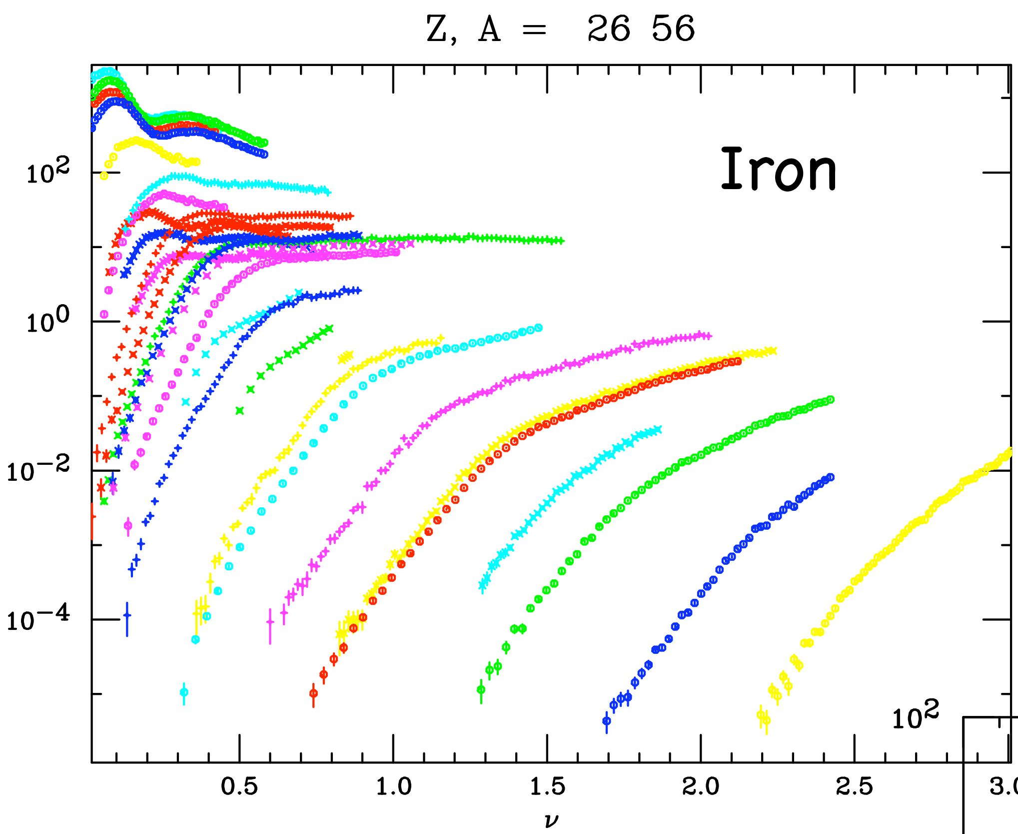
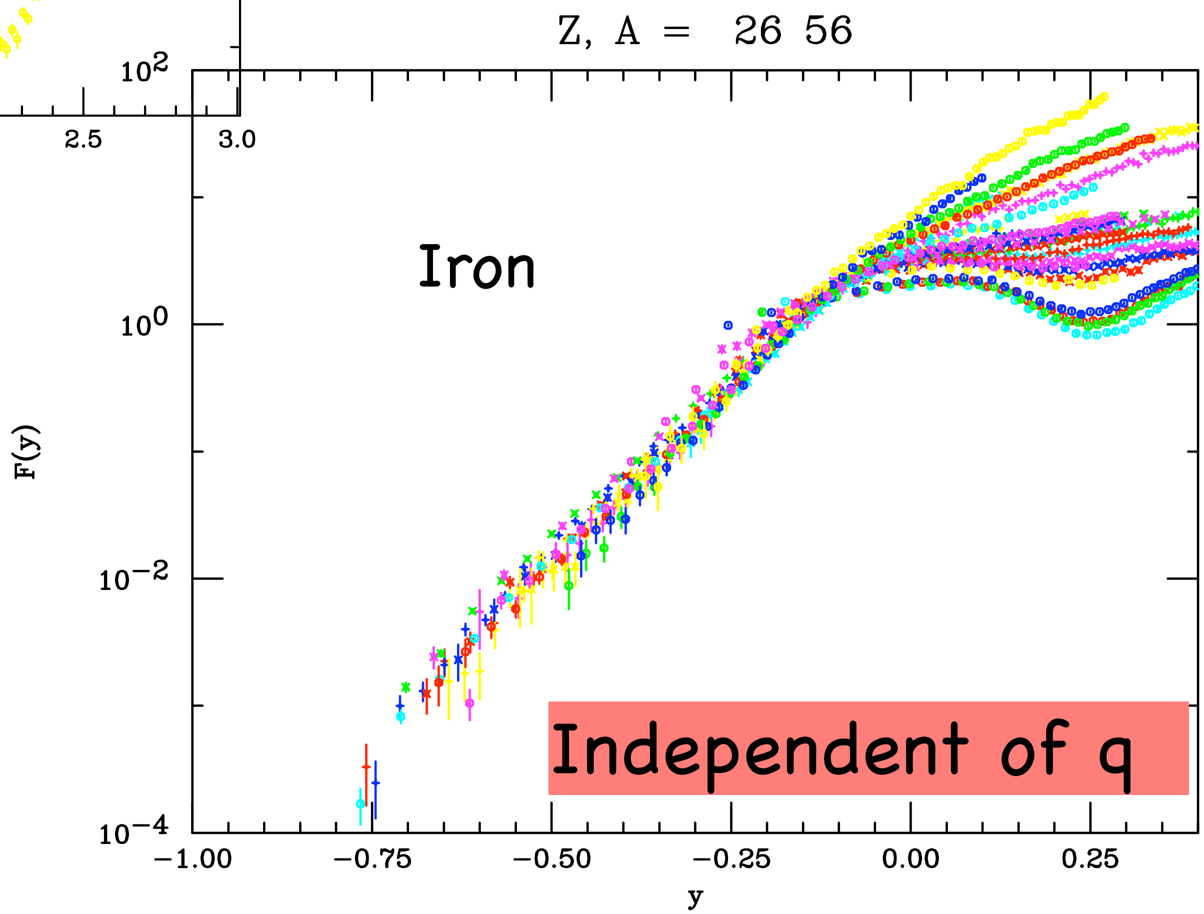




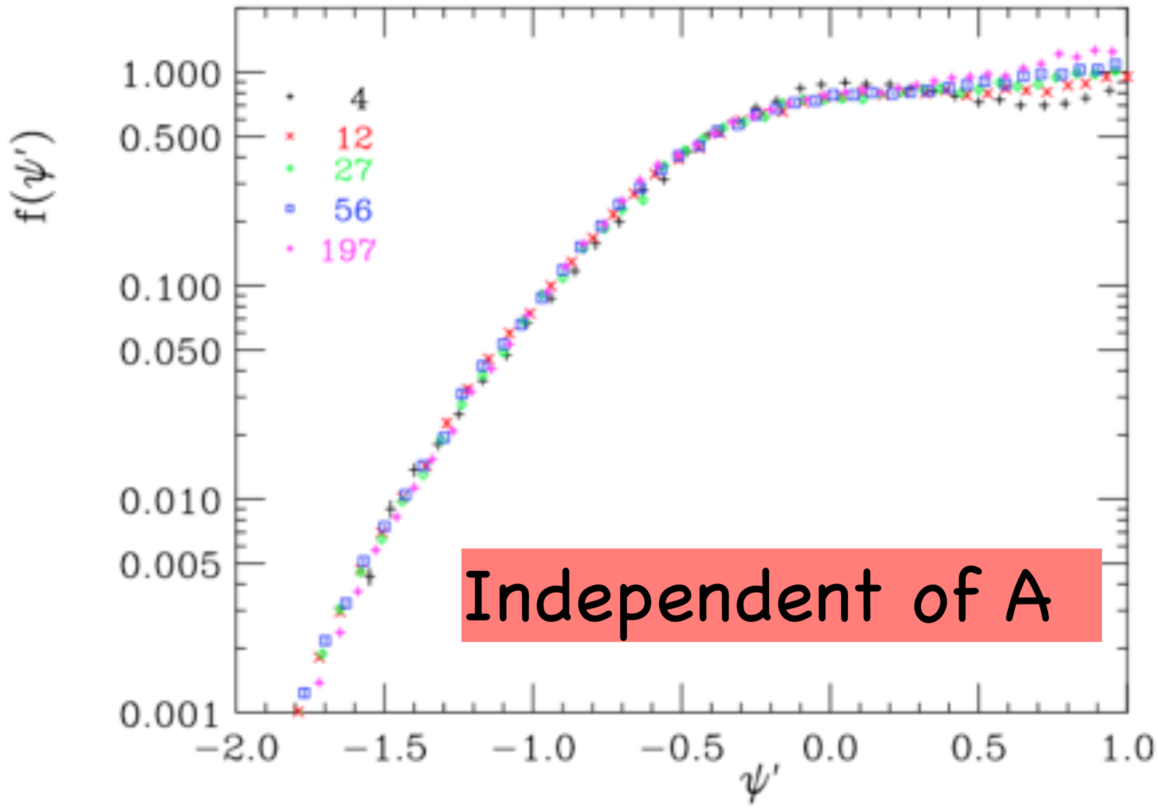
Presented in this way F(y) demonstrates a independence of q

Scaling of a second kind independent of A

$$k_A = \sqrt{< k^2 >_A} = k_f$$

$$f(q, y) \equiv k_A \cdot F(q, y)$$

$$\psi \simeq y / k_A$$

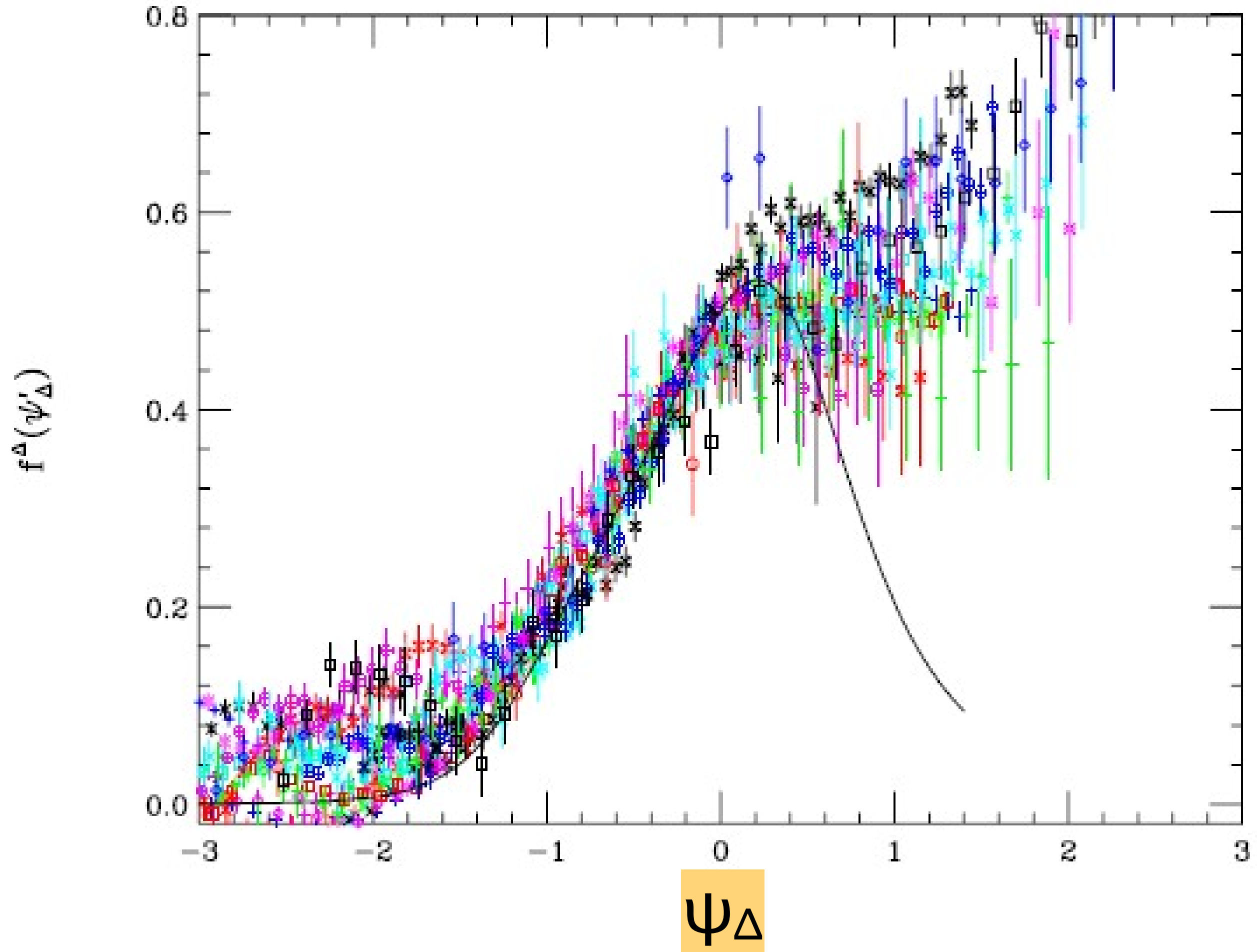


Super Scaling - independent of A and q

There exists only one universal (QE) scaling function, f^{QE}_L longitudinal response, which contains the nuclear physics information of the process

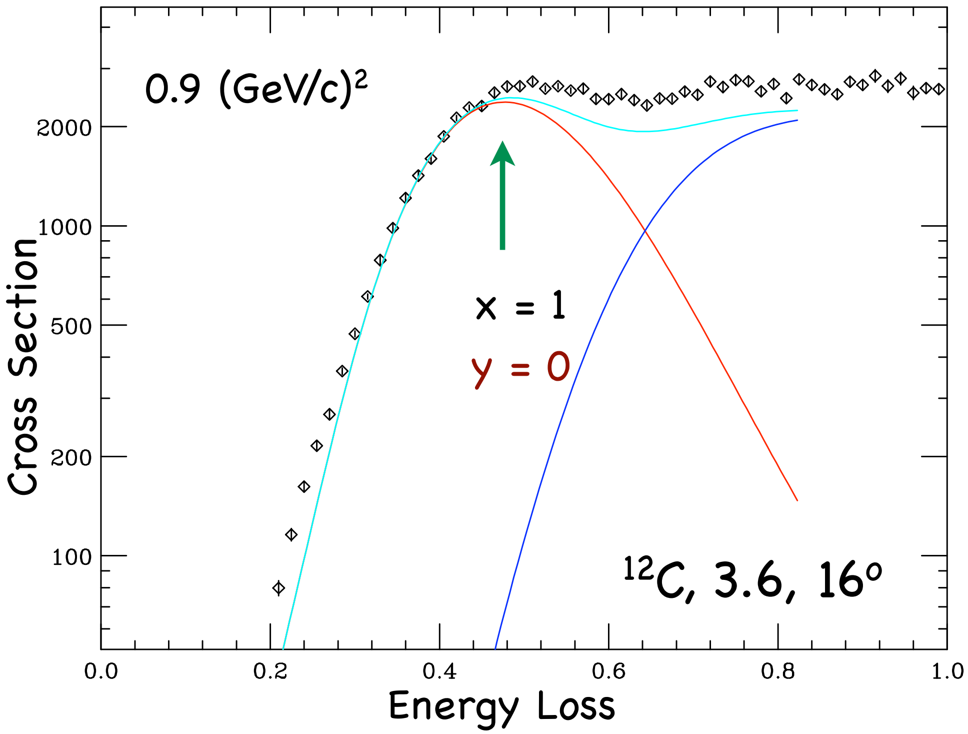
I Sick, T.W. Donnelly, C.F. Williamson, C. Maieron, J.E. Amaro, M.B. Barbaro, A. Molinari, A. Antonov, M. V. Ivanov, M. K. Gaidarov, J.A. Caballero, E. Moya de Guerra,

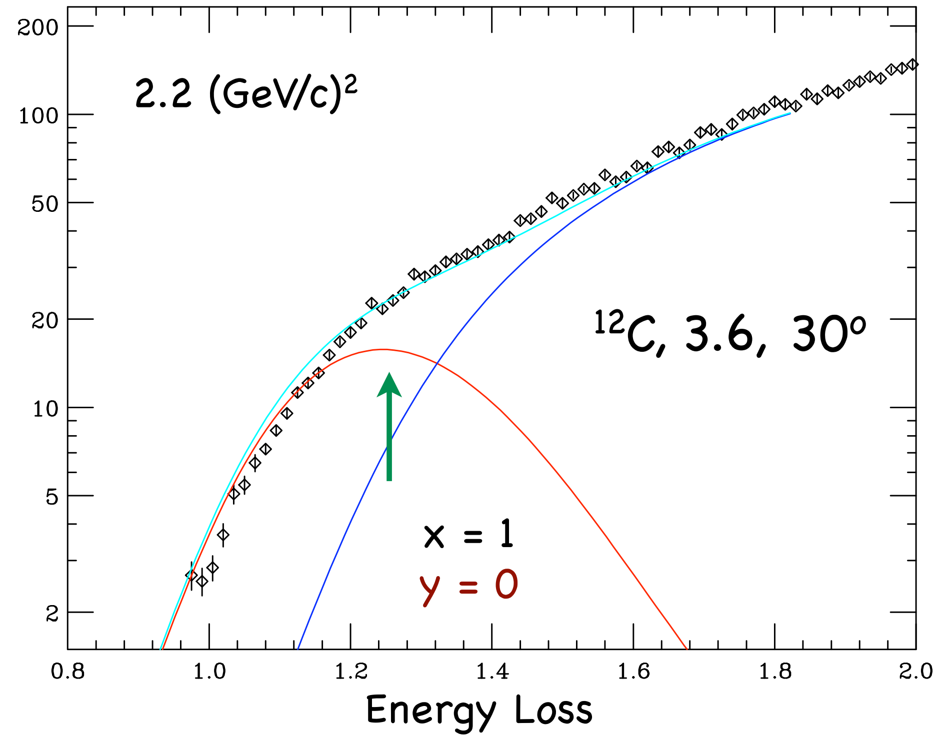
Beyond the QE-Peak: Delta Region



Inclusive electron scattering from ^{12}C and ^{16}O in the Δ regions -- energies extending from 300 MeV to 4 GeV and scattering angles from 12 to 145 degrees, Amaro et al, PRC 71, 015501(2005)

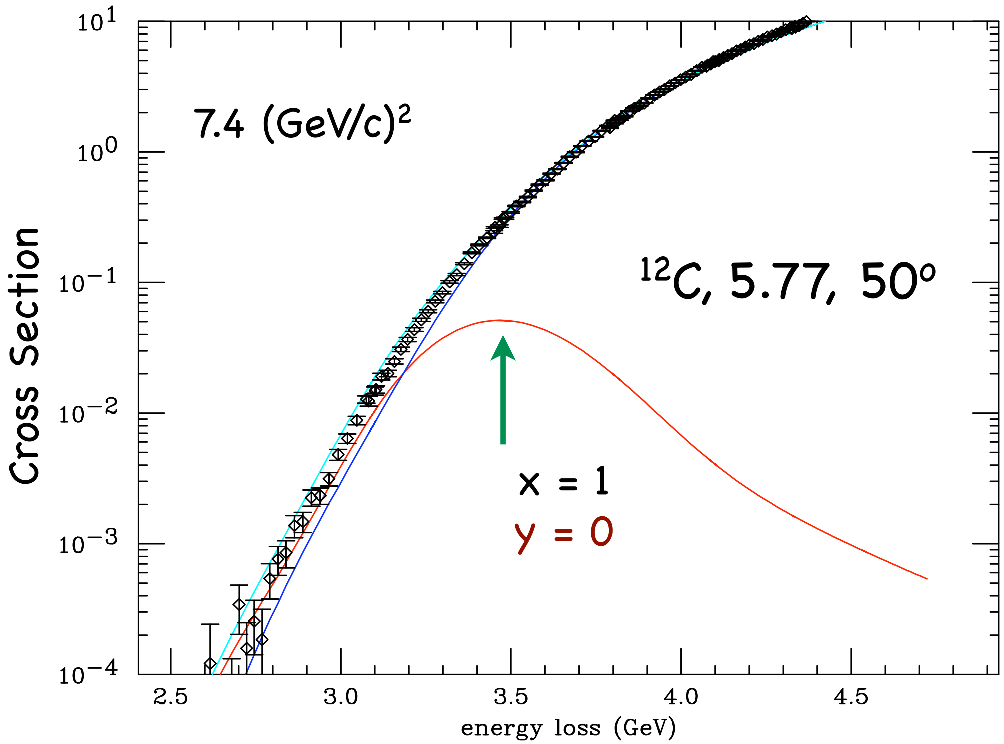
Inelastic contribution increases with Q^2





DIS begins to contribute at x > 1

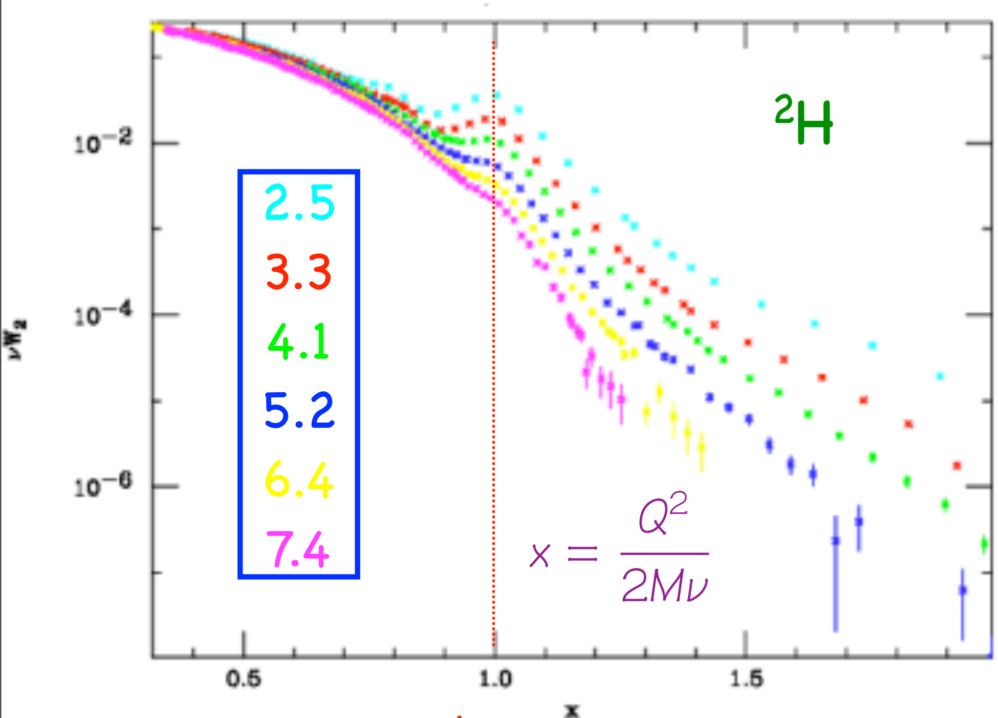
Convolution model



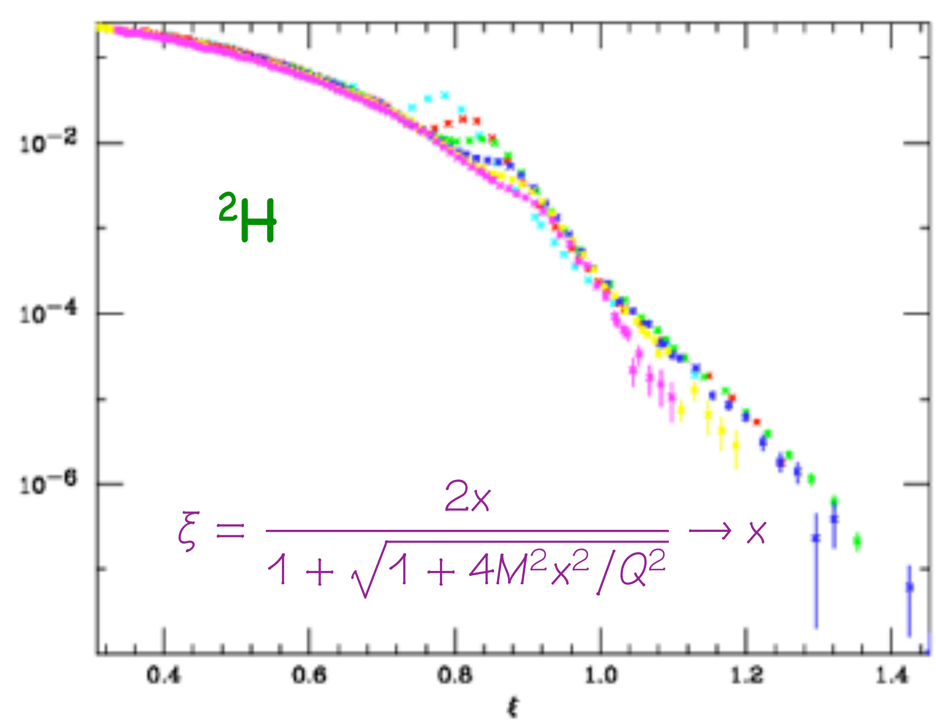
We expect that as Q^2 increases to see evidence (x-scaling) that we are scattering from a quark at x > 1

x and ξ scaling

Remarkably when the data is presented is presented in terms of the nuclear inelastic structure functions evidence of scaling emerges.

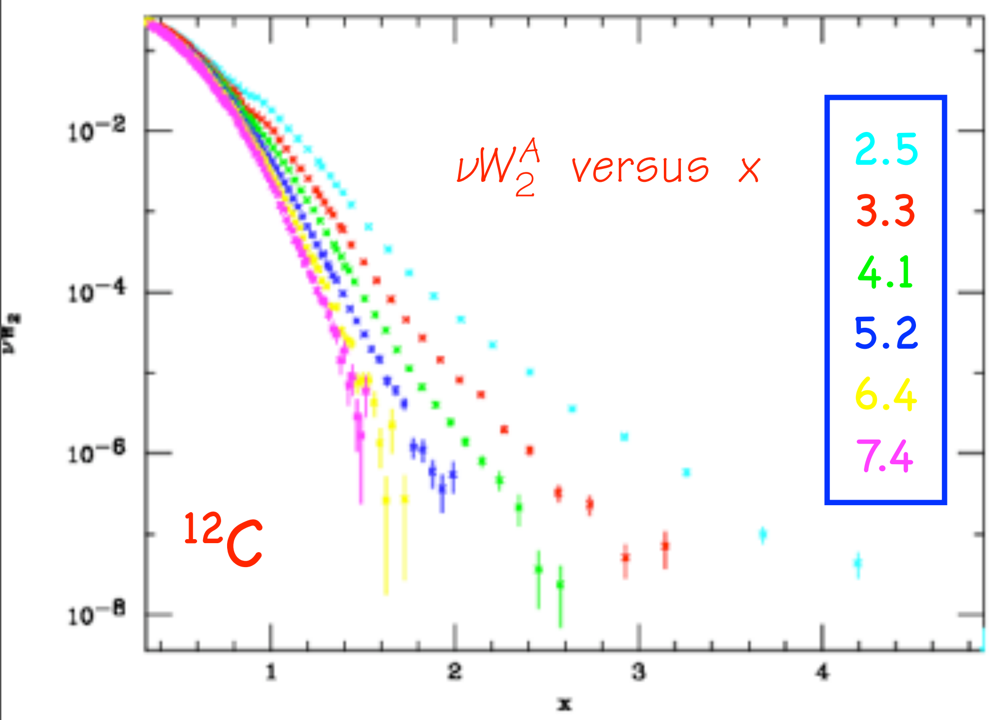


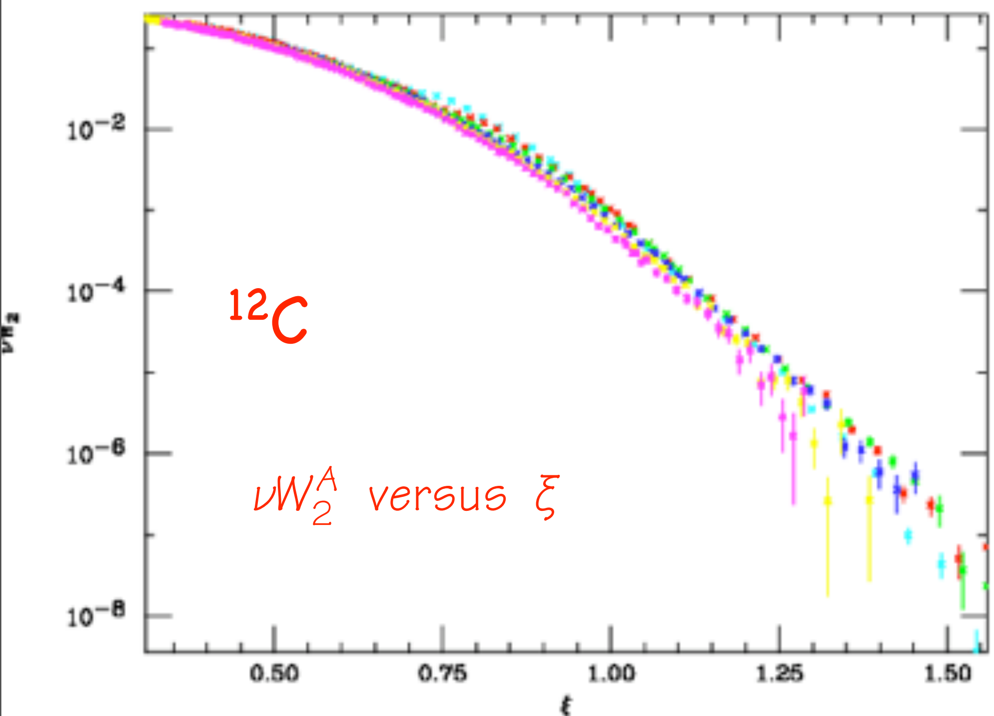
νW_2^A versus x



νW_2^A versus ξ

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





Especially for the heavier nuclei

ξ (fraction of nucleon light cone momentum p^+) is proper variable in which logarithmic violations of scaling in DIS should be studied.

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

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

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

Can we extract nuclear pdfs in this region?

A 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

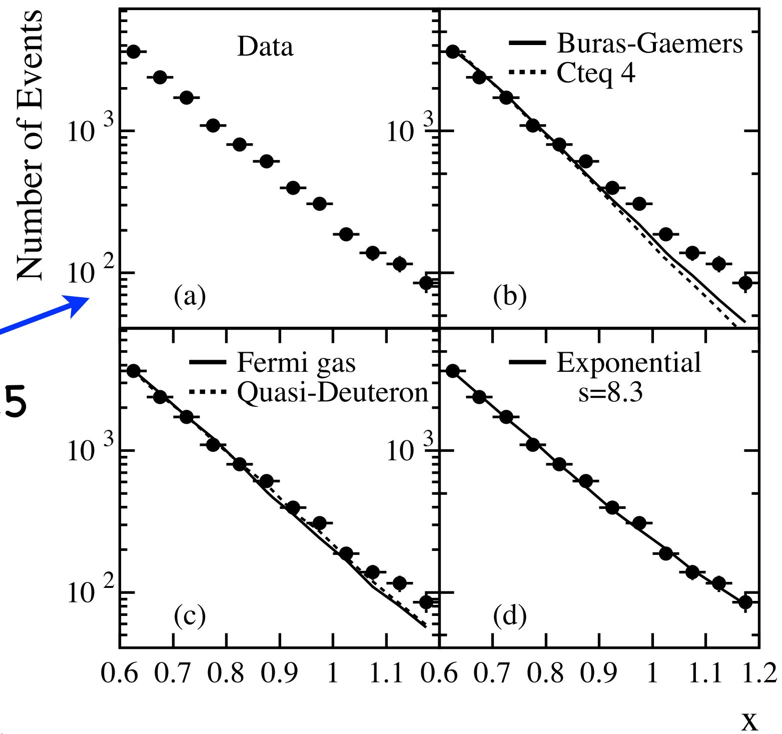
BCDMS (μ-Fe): $F_2(x) \propto e^{-sx}$ s = 16

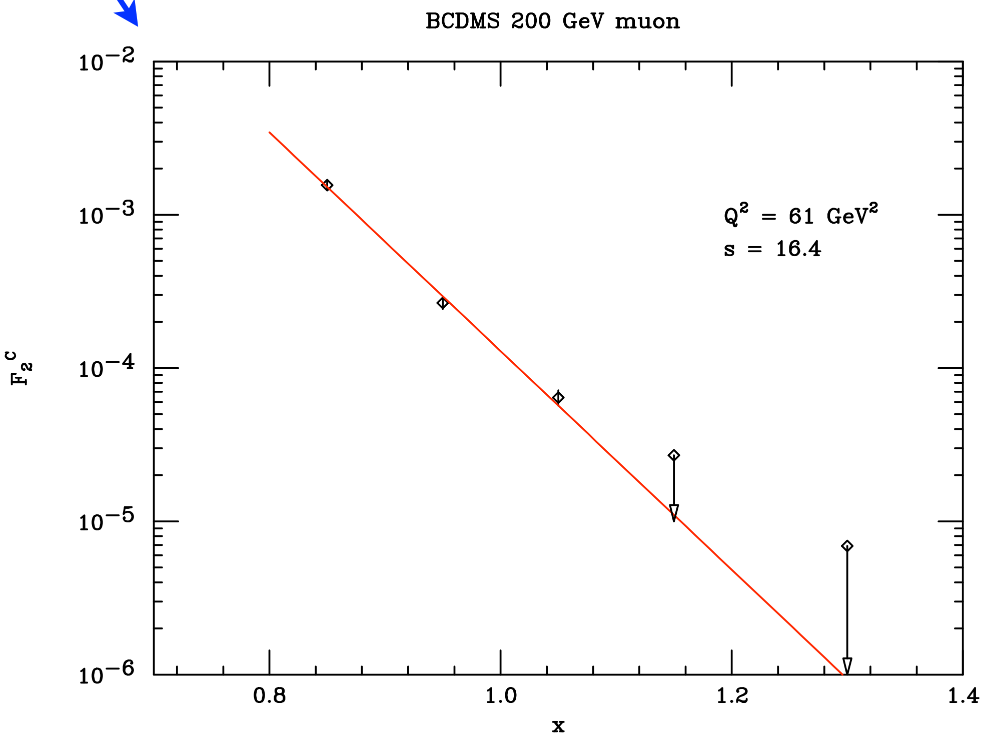
Poor resolution, limited x range

Low statistics

125

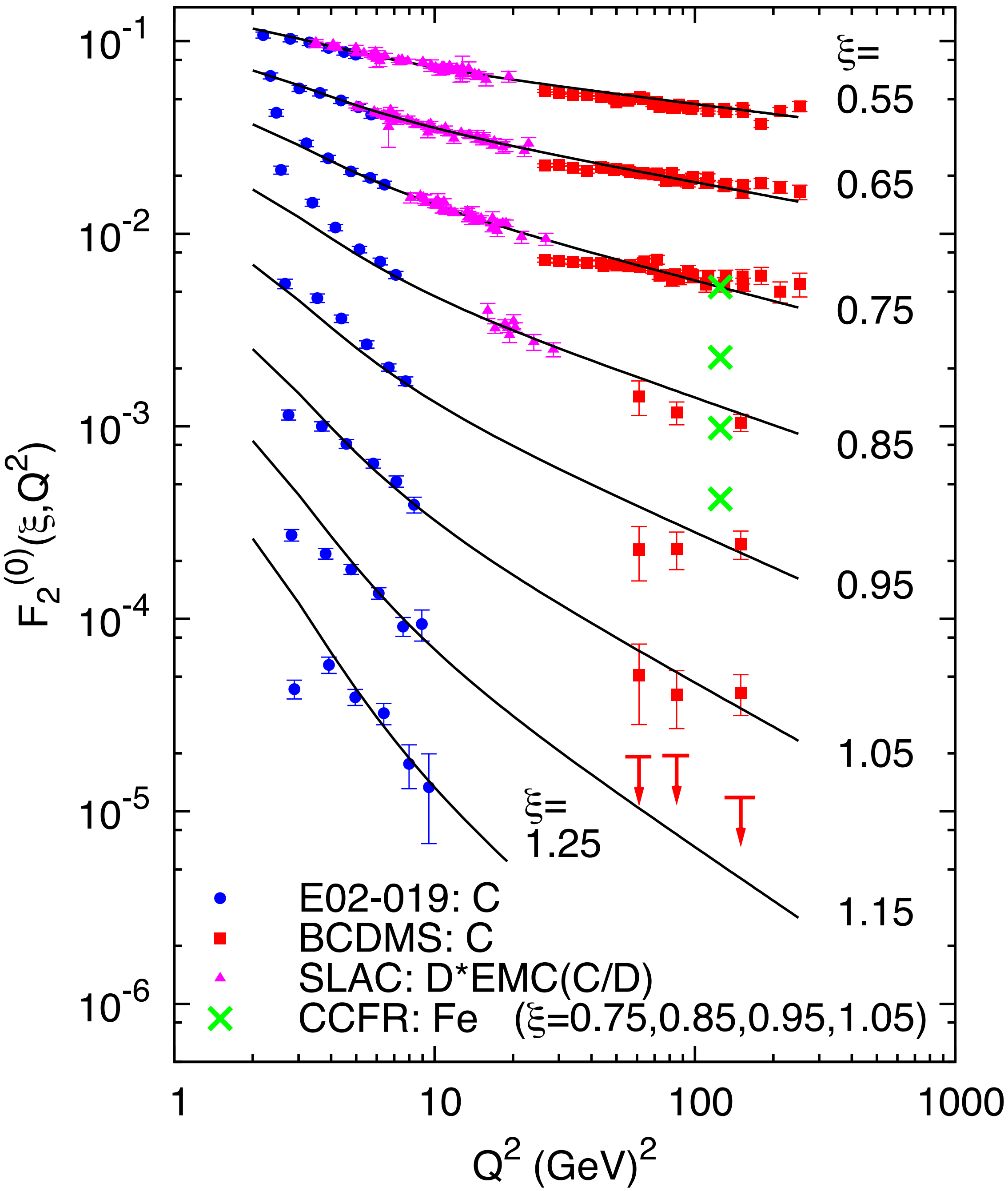
60 (50-200)





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.

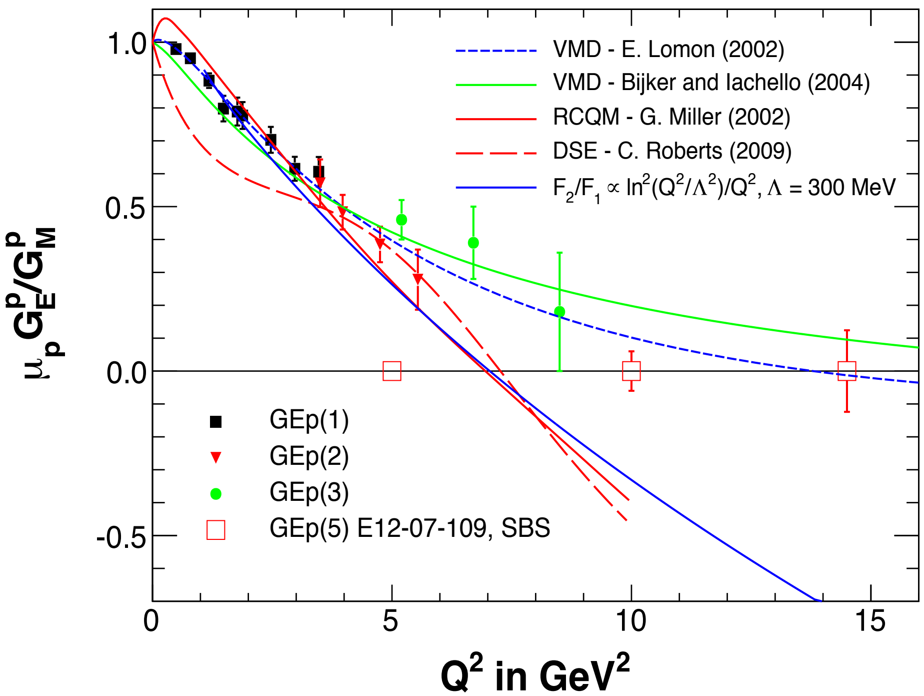


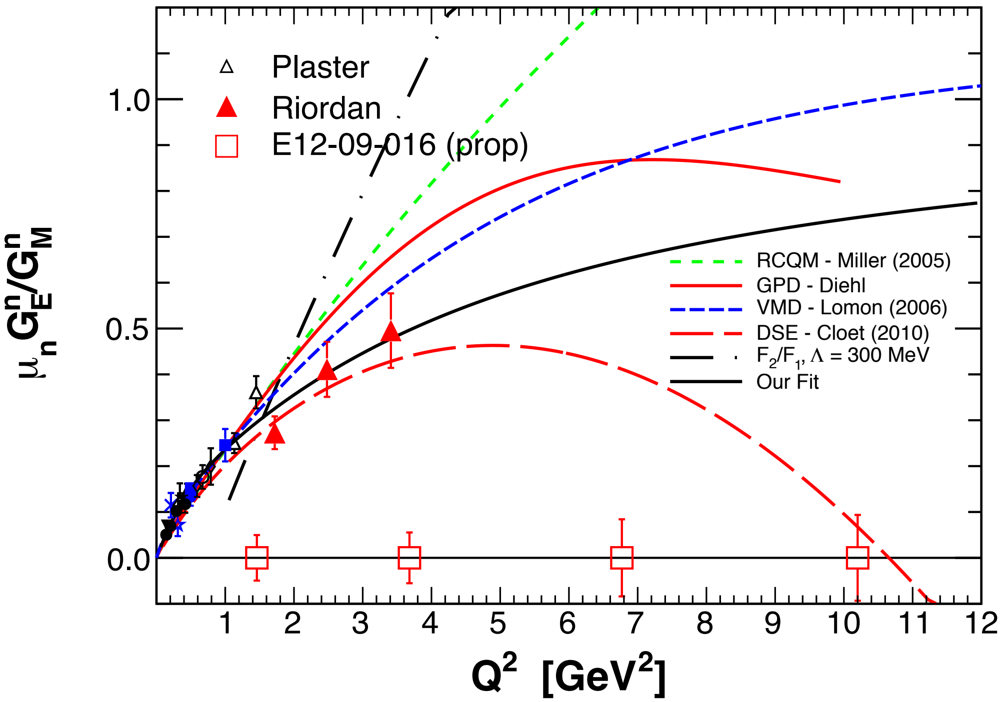
Application of 'target mass corrections"

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

Fomin et al., Phys. Rev. Lett.105:212502,2010

In any effort at prediction you must have the e/m FF right and there have been surprises

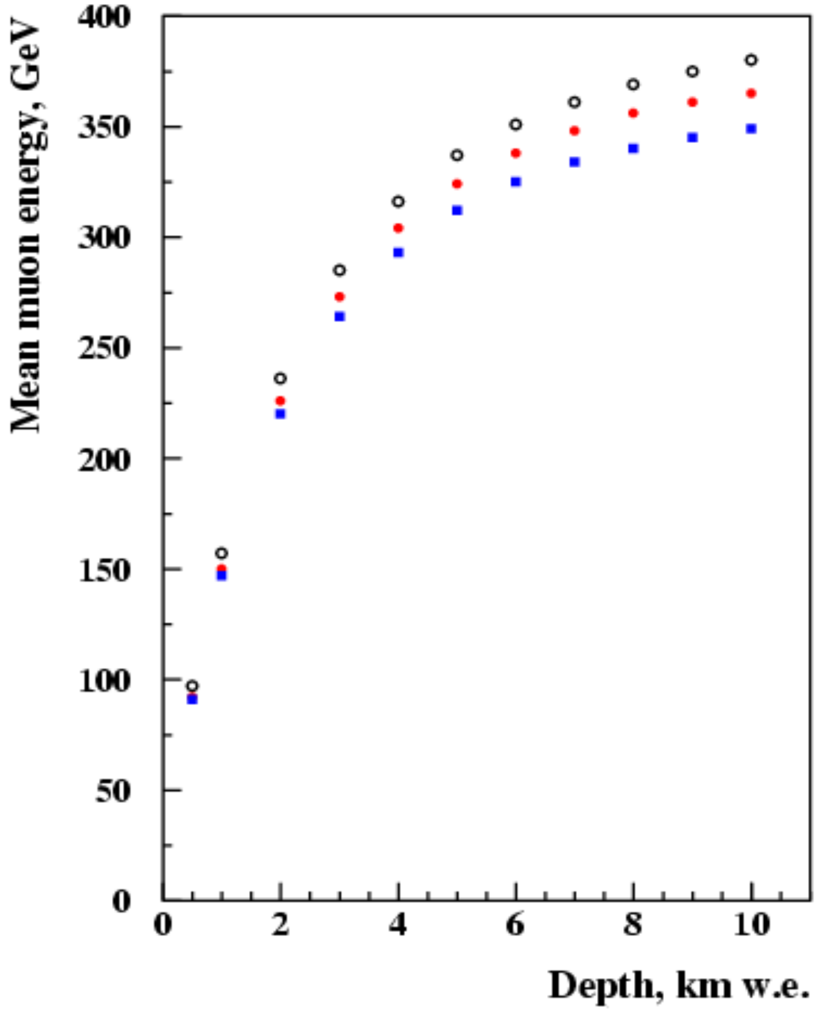




$$\frac{d\sigma}{d\Omega} = \sigma_{\rm NS}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2(\theta/2)\right],$$

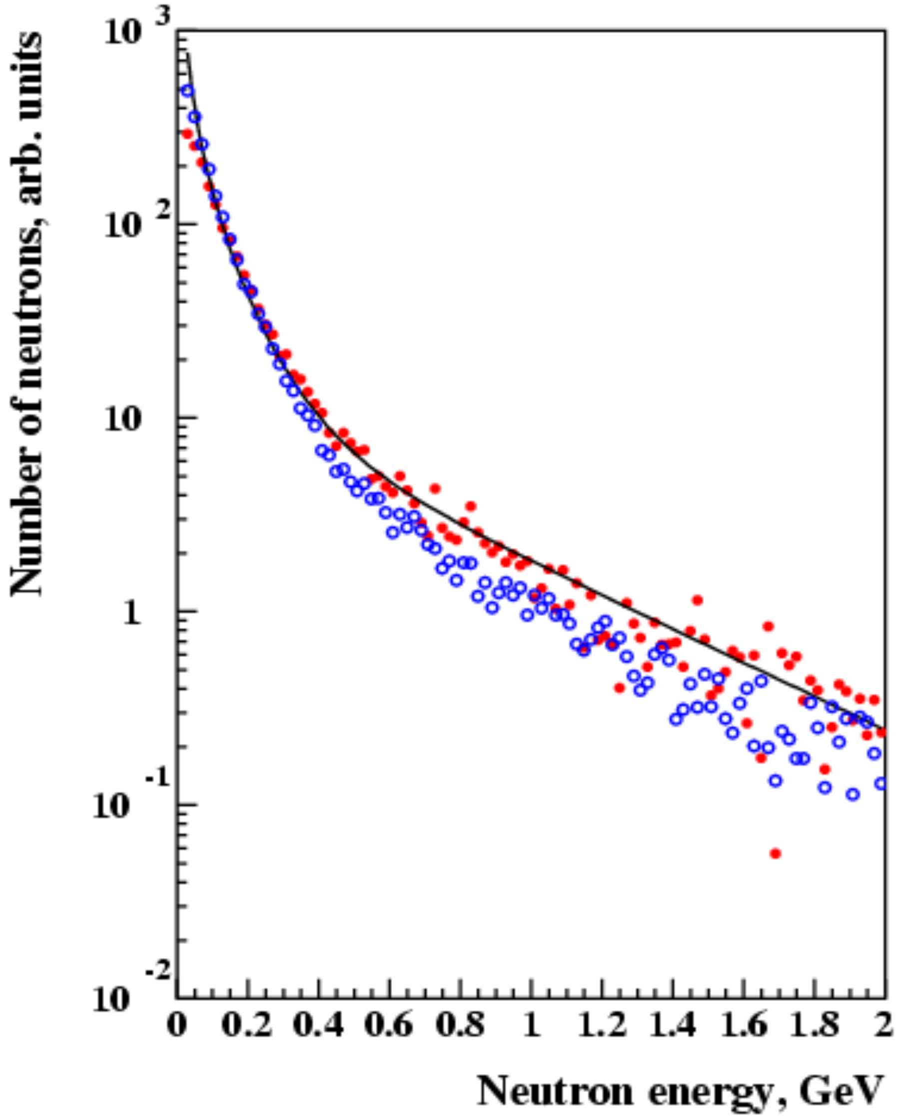
At a Q^2 = 6 GeV/c^2 you would make about a 6% error ignoring the electric form factor of the neutron

Muon mean energy



Talk by V. A. Kudryavtsev, 2002

Neutron spectrum



p = 0 p = 2.75

What this suggests to me.

Finish

There is a significant body of experimental and theoretical work on inclusive electron scattering which has direct application to muon scattering

The e/m community is contributing to experimental studies of neutrino oscillations at GeV energies MiniBooNE and K2K/T2K experiments. These involve neutrino energies of several GeV.

Lots of things to worry about - correct nucleon FF, medium modifications, SRC, FSI .. but it appears that scaling holds over a very large range of Q^2 and x which should allow reliable predictions of the cross sections

I can not offer much on the fate of the neutron - there transport codes that are proving useful to the neutrino community for just this problem - GIBUU.

Any reliable calculation for muon scattering must be tested against electron scattering data

Inclusive quasi-elastic electron-nucleus scattering.
O. Benhar , DD, I Sick, Rev. Mod. Phys. 80 (2008) 189-224

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

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Quasielastic Electron Nucleus Scattering Archive

Welcome to Quasielastic Electron Nucleus Scattering Archive

In connection with a review article (Quasielastic Electron-Nucleus Scattering, by O. Benhar, D. Day and I. Sick) to be submitted to Reviews of Modern Physics, we have collected here an extensive set of quasielastic electron scattering data in order to preserve and make available these data to the nuclear physics community.

We have chosen to provide the cross section only and not the separated response functions. Unless explicitly indicated the data do not include Coulomb corrections.

Our criteria for inclusion into the data base is the following:

1. Data published in tabular form in journal, thesis or preprint.
2. Radiative corrections applied to data.
3. No known or acknowledged pathologies

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

In the infrequent event that corrections were made to the data after the original publications, we included the latest data set, adding an additional reference, usually a private communication.

As additional data become known to us, we will add to the data sets.

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