Inclusive Electron Scattering from Nuclei at $x \geq 1$ with a 12 GeV CEBAF[‡]

- Wealth of Physics

  QES with Q^2 as a "knob" to
  DIS dial the dominant process

- Both QES and DIS share the underlying nuclear physics of the initial state ($S(\underset{\sim}{k}, E)$) and both potentially can expose the Short Distance behavior

- QES ⇒ scaling in $\underline{\underline{y}}$
  ⇒ momentum distribution

- DIS ⇒ scaling in x, ξ
  ⇒ structure functions behavior in nuclear medium
  (tests of EMC models)

‡ 11 GeV in Hall C

at $Q^2 >>$ we can expose the quark-gluon structure of the dominant dynamics (at large x => SRC)

at $Q^2 >>$ and $x \geq 1$ there are suggestions that other physics play a role

- Color transparency
- Duality ($\gamma(q) \stackrel{?}{\equiv} \gamma(qqq)$) John Arrington talk
- Parton recombination

The inclusive nature of these studies makes disentangling all the different pieces a challenge but ...

Q^2 range helps a lot

- Some data
- y scaling
- ξ scaling
- argue that ratio σ^A/σ^D exposes the SRC
- show what we expect the σ to look like (at what Q^2 DIS begins to dominate QES)
- finish w/ $x - Q^2$ range we could cover with 11 GeV

Deep Inelastic Scattering

At $Q^2 >>$

virtual photon probes nucleon

on time scale $t_0 \sim \mathcal{O}\left(\frac{1}{\sqrt{Q^2}}\right)$.

$t_0 << t_{\substack{\text{Strong} \\ \text{Interaction}}}$

nucleon is essentially "frozen"

light-cone dominated

As Q^2 increases we resolve more

and more of quark gluon structure.

Despite being "frozen" the nucleon

structure functions are systematically

modified by the presence of other nucleons.

EMC! $0 < x < 1$

$\langle r_{NN} \rangle \sim 2 \times r_N$

Overlap of quark gluon wave function

- In the nucleus $0 < x < A$.

In Bjorken limit $x > 1$ DIS tells us the virtual photon scatters incoherently from quarks.

- Quarks can obtain $x > 1$ by abandoning the confines of the nucleon; <u>multi quark configurations</u>. Or by being <u>correlated with a nucleon of high momentum</u>. [SR interaction]

deconfinement
color conductivity

- DIS at $x > 1$ is a filter that selects out those nuclear configurations in which the nucleons (quark gluon wave functions) overlap.

Not surprising that there exists a relationship between large x behavior and elastic form factors.

Drell - Yan - West relation

$$\nu W_2 (x \to 1) \sim (1-x)^{2N-1}$$

where N is the asymptotic behavior of elastic form factors, $G_m(Q^2) \sim (Q^2)^{-N}$

For proton $N = 2$ (dipole)

$$\nu W_2 (x \to 1) \sim (1-x)^3$$

Constituent Counting rules

exponent depends on minimum number of elementary constituents in hadronic bound system

This suggests that the large x behavior of the nuclear structure function $F_2^A(x>1)$ will tell us about the minimum number of constituents in the configuration that gives rise to the large x.

- correlated nucleons
- multiquark objects 6, 9 ...

quasi elastic electron-nucleus scattering
(e,e') at 500 MeV, 60°, $\vec{q} \simeq 500$ MeV/c

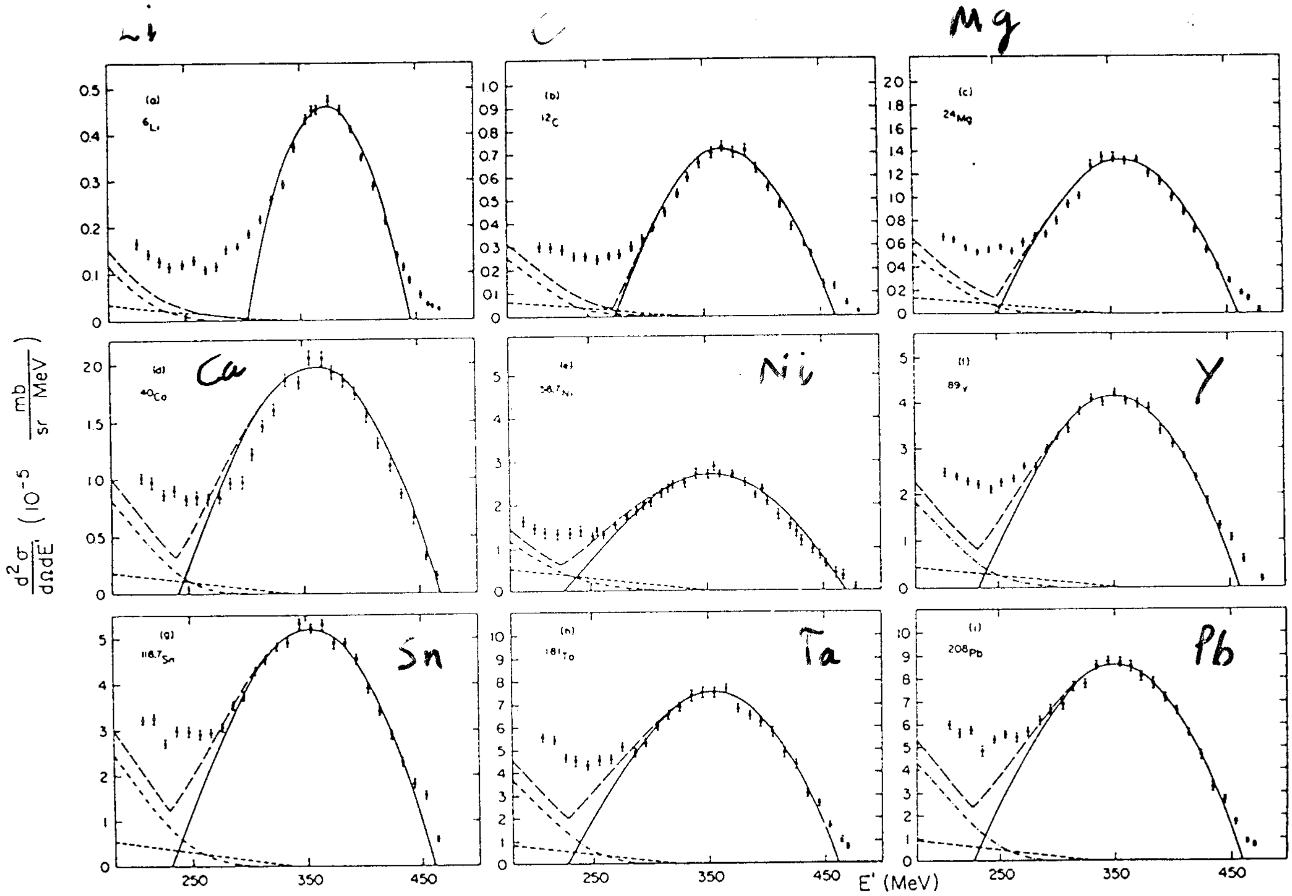
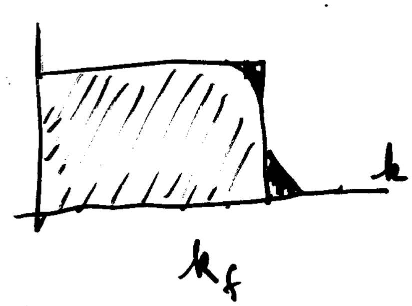


Fig. 4. Spectra of 500-MeV electrons scattered at 60° by various nuclei. The solid curve is a fit by the Fermi gas model which yielded the values for k_F (Fermi momentum) and $\bar{\varepsilon}$ (average separation energy) listed in Table I. Contributions from s-wave π production (short-dashed curve) and $\Delta(1236)$ excitation (dot-dashed curve) are also shown, together with the total result (long-dashed curve) (from Whi+74).

Fermi gas model $\rho(k)$

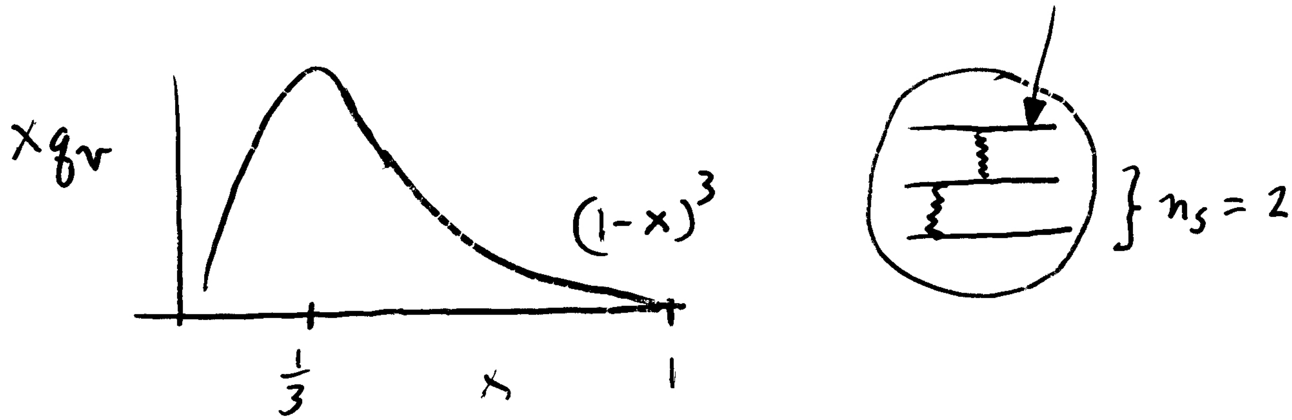


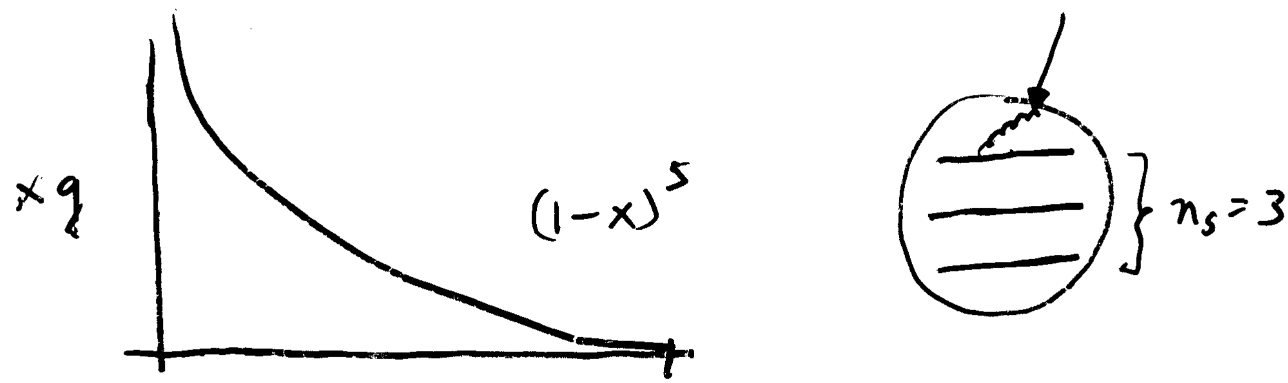
Estimates of $f_i(x, Q^2)$

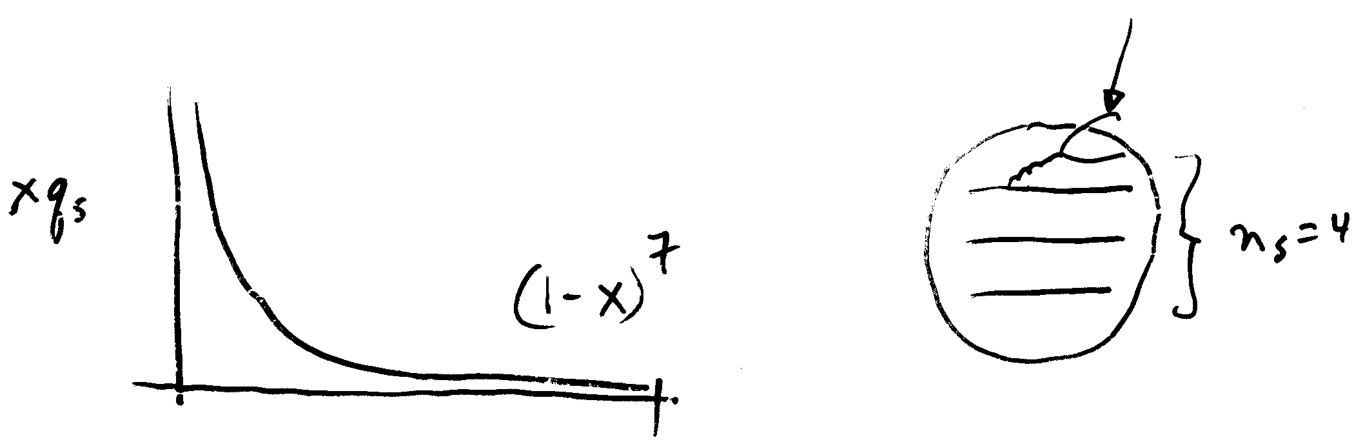
$x \to 1$ behavior

$$f_i(x) \sim (1-x)^{\underline{2n_s - 1}}$$

n_s = minimum # of spectators







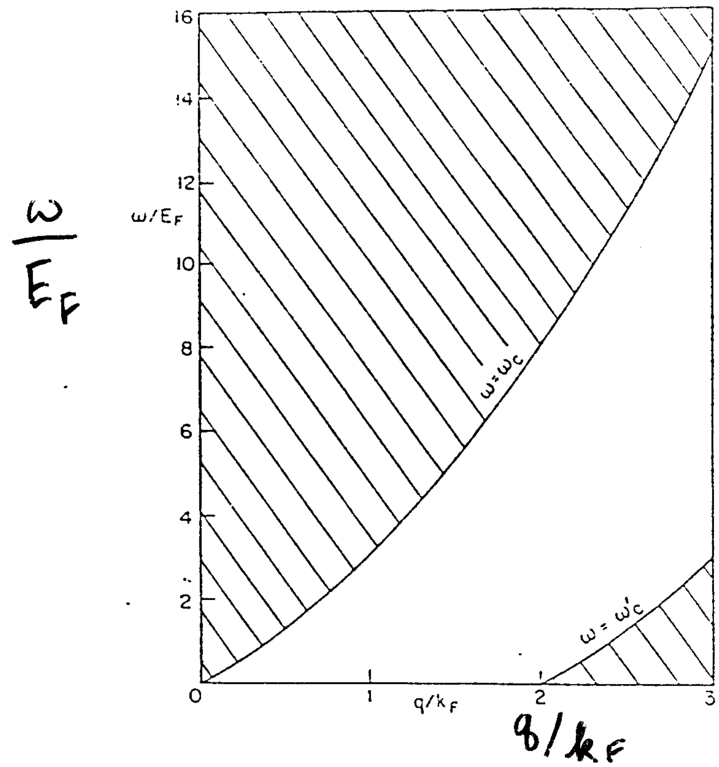


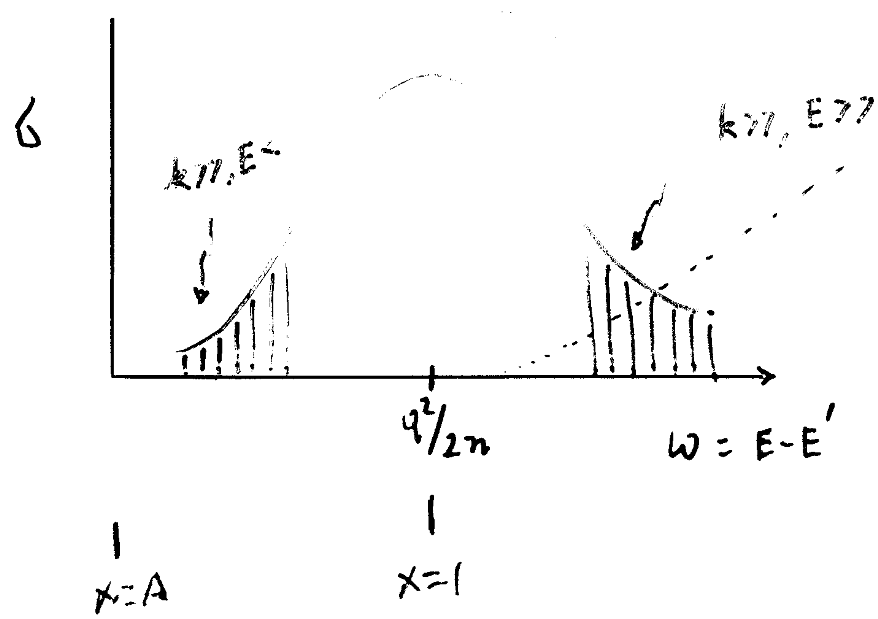
Figure 1: Shaded region in q-ω plane is region where scattering is due solely to correlations (from Ref. 7).

Correlations

Czyz ; Gottfried

$$\omega_c(q) = \frac{(k+q)^2}{2m} + \frac{q^2}{2m}$$

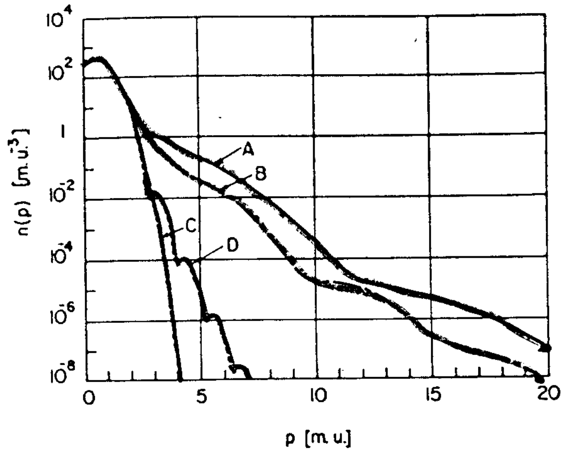
$$\omega_c'(q) = \frac{q^2}{2m} - \frac{q k_f}{m}$$



True for DIS as well
specific pieces of initial state is probed at different x

Momentum Distribution with and without correlations

Momentum distributions for ^{16}O calculated by Van Orden et al. for correlated (A,B) and uncorrelated (C,D) wave functions.



- short distance behavior
- inside nuclear volume
- FSI are inescapable – they are generated by the interaction responsible for the short range behavior

- MEC, isobar components of nuclear w.f. have same dynamical source as short range correlations: mutual interaction among hadrons.

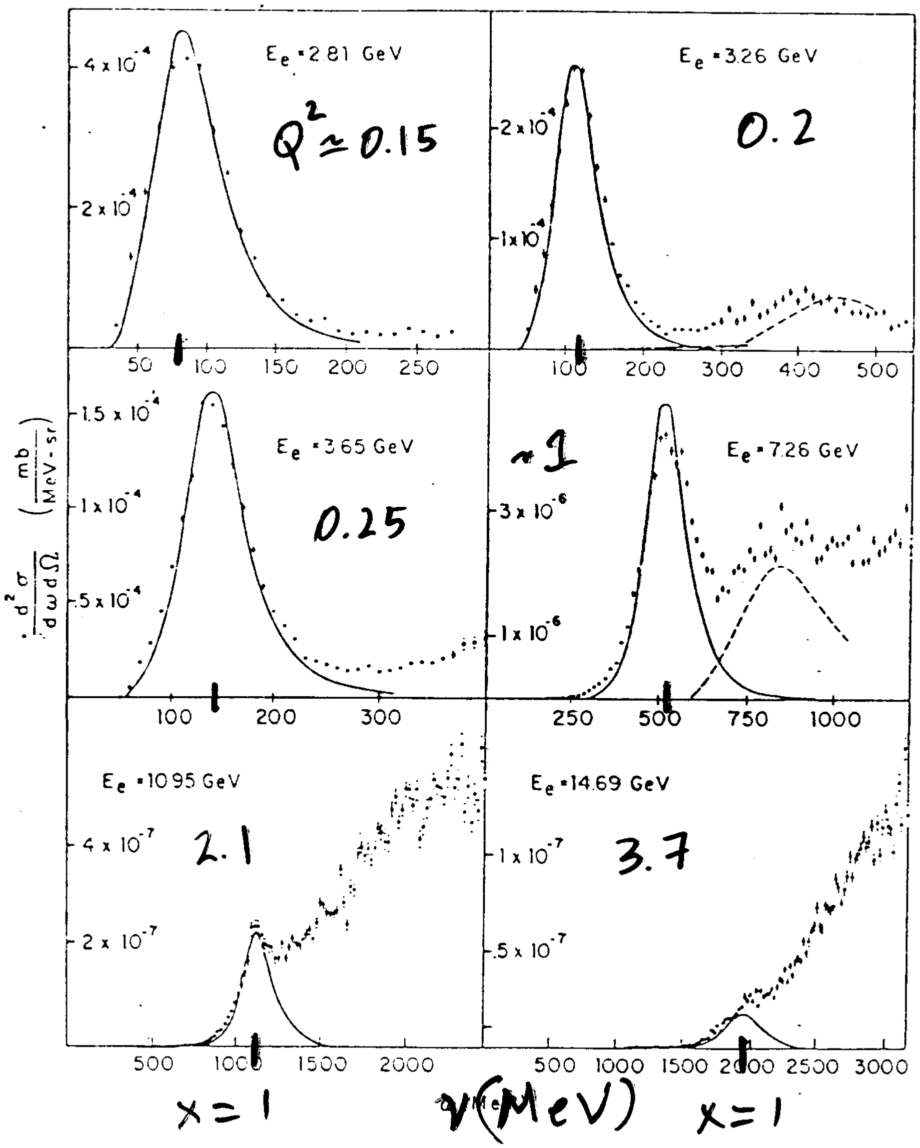
- One experiment at one q is insufficient (e,e'), $(e,e'p)$, $(e,e'2p)$ ... over a wide range of q will be necessary.

Transition from QES to DIS

$$\text{QES} \propto \int d\vec{k} \int dE\, \sigma_{ei}\, \underline{S_i(k,E)}\ ; \quad \sigma_{ei} \text{ goes as FF}$$

$$\text{DIS} \propto \int d\vec{k} \int dE\, W_{1,2}^{p,n}\, \underline{S_i(k,E)}\ ; \quad \nu W_2, MW_1 \sim \ln Q^2$$

$^3He(e,e')$



SLAC E121 ^3He

Nucleons for $x > 1$; scaling in y.

$\boxed{\text{Y scaling}}$ At large q

$$\frac{d^2\sigma}{d\Omega dE'} = \sum_{ei} \tilde{\sigma}_{ei} \cdot K \cdot F(y)$$

$$F(y) = 2\pi \int_{-y}^{\infty} k\,dk \int_{0}^{E_{max}} dE\, S(k,E)$$

Note: if $E_{max} = \infty$ then

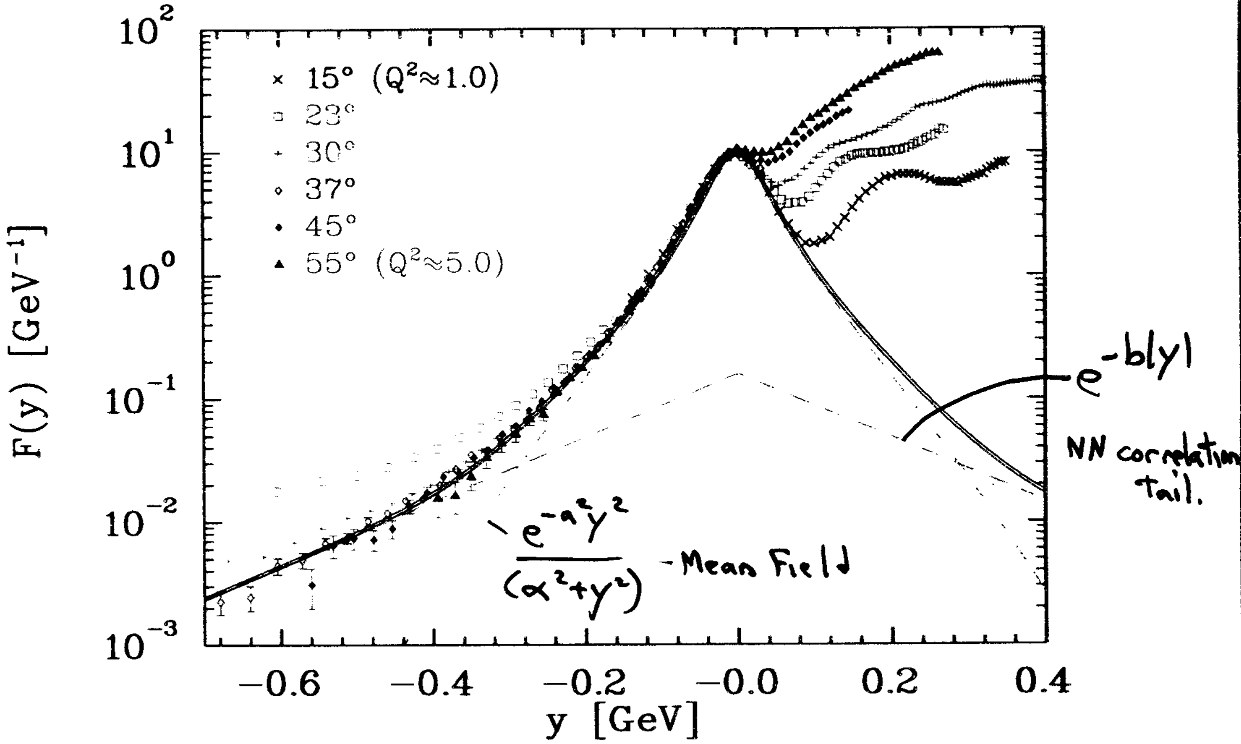
$$F(y) = 2\pi \int_{-y}^{\infty} k\,dk\, n(k)$$ {longitudinal momentum distribution}

and QES would provide a direct measure of $n(k)$.

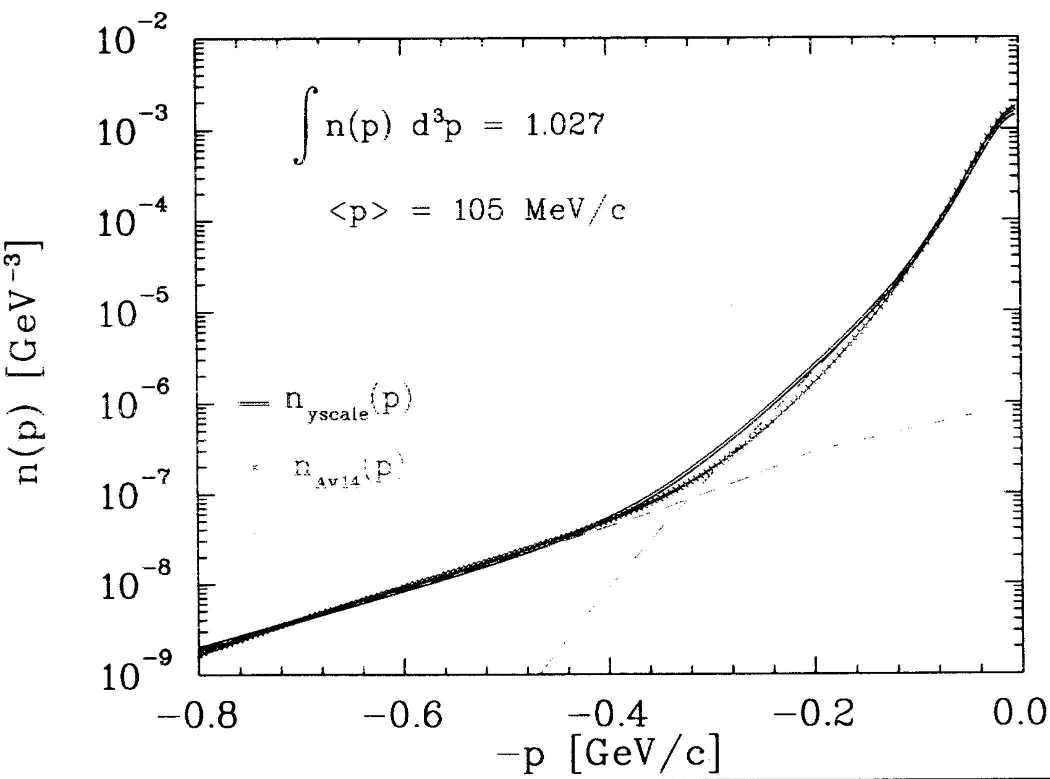
① even at $q \gg$ full strength of $S(k, E)$ is not integrated at large y.

② FSI.

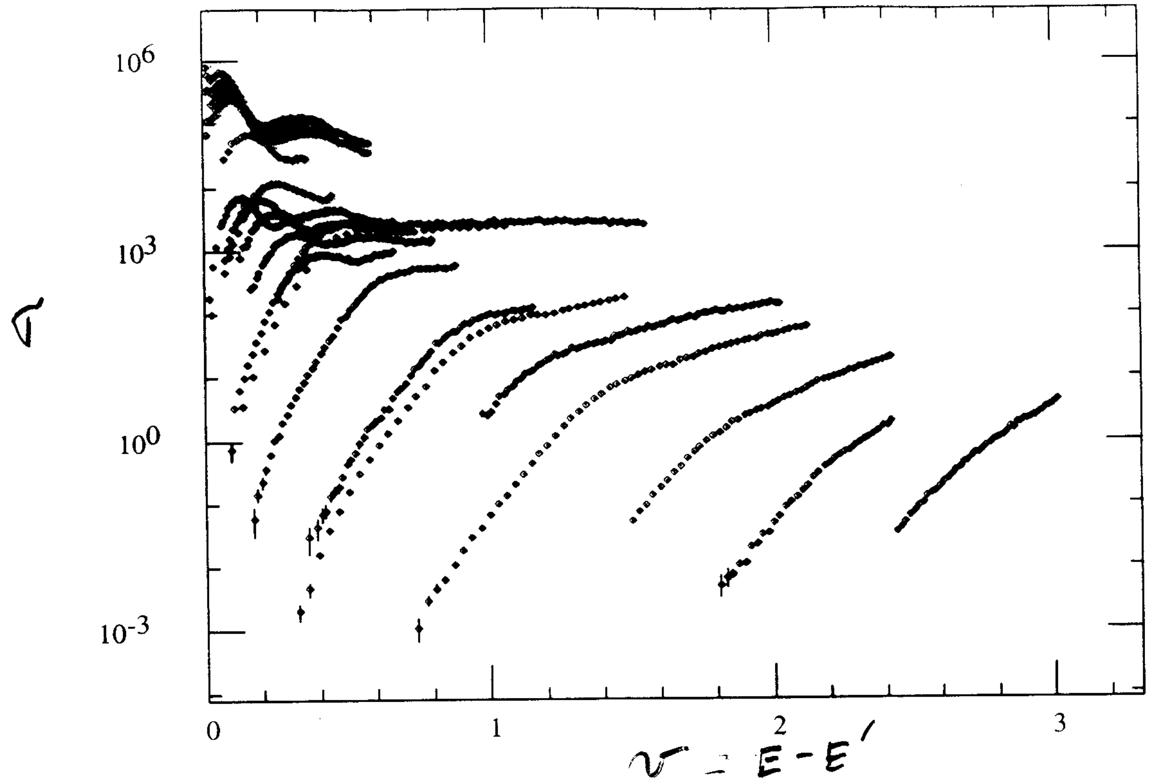
D(e,e') - preliminary



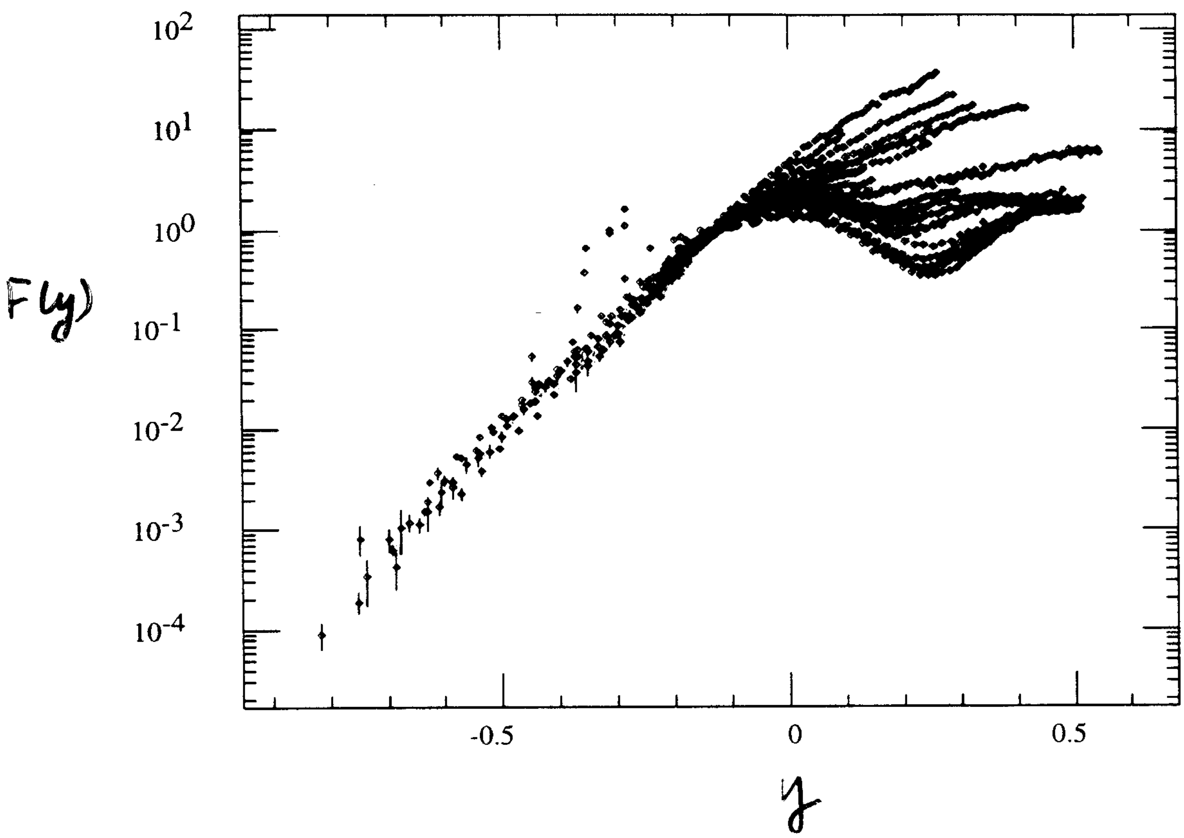
$$n(p) = \frac{-1}{2\pi p}\frac{dF(p)}{dp}$$



^{12}C

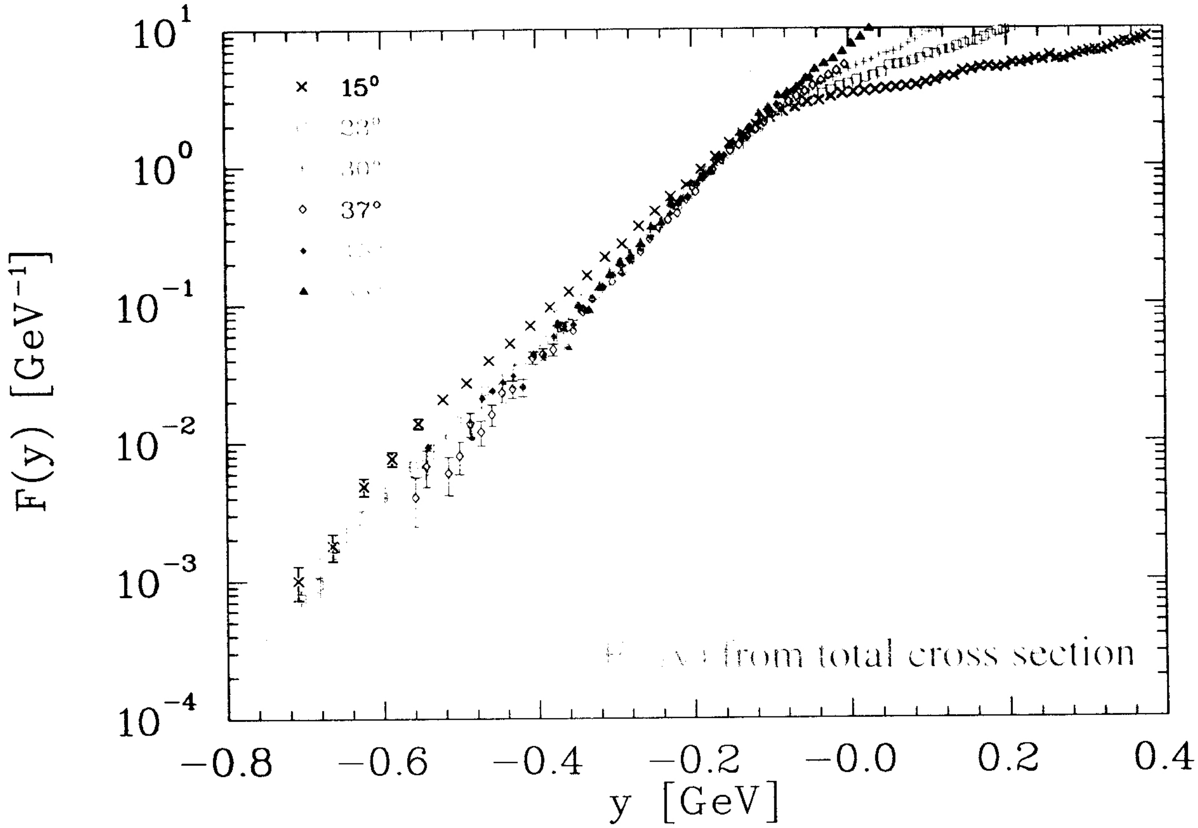


10^6
10^3
10^0
10^{-3}
σ
0
1
2
3
$\nu = E - E'$

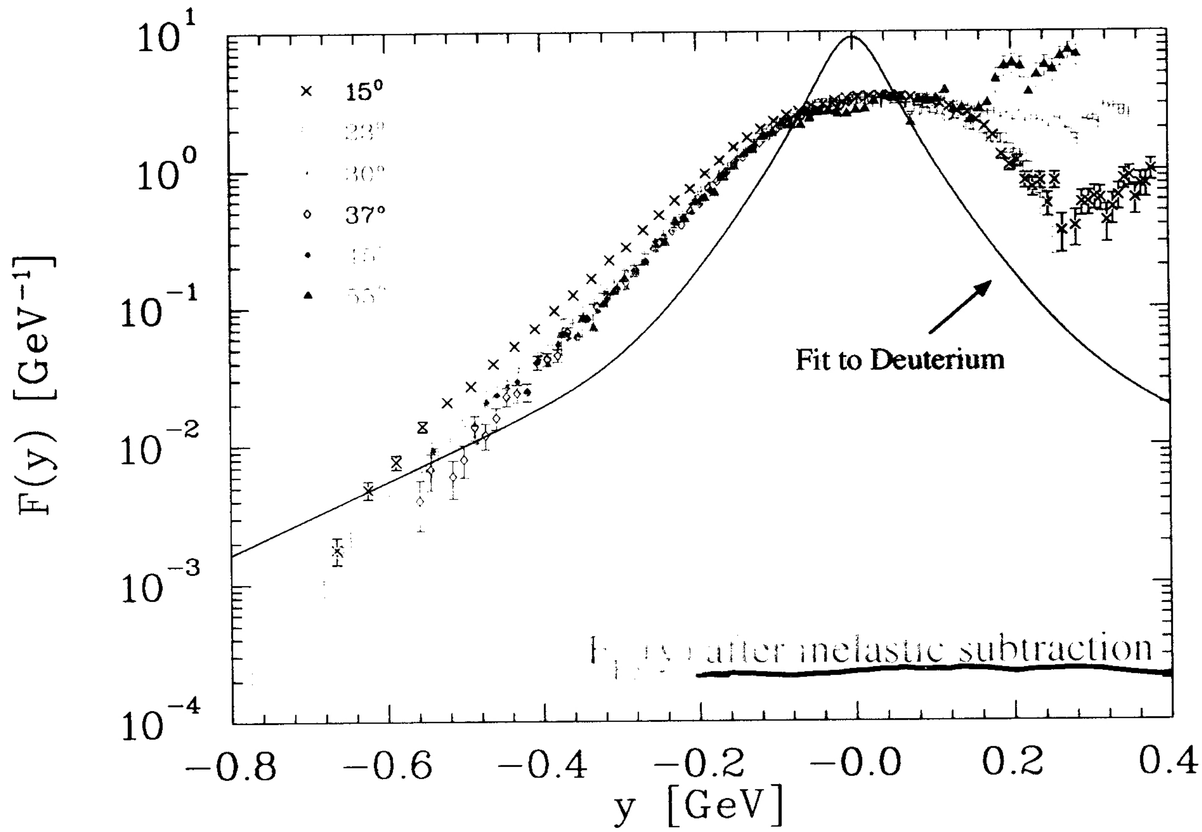


10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$F(y)$
-0.5
0
0.5
y

F(y) for Iron

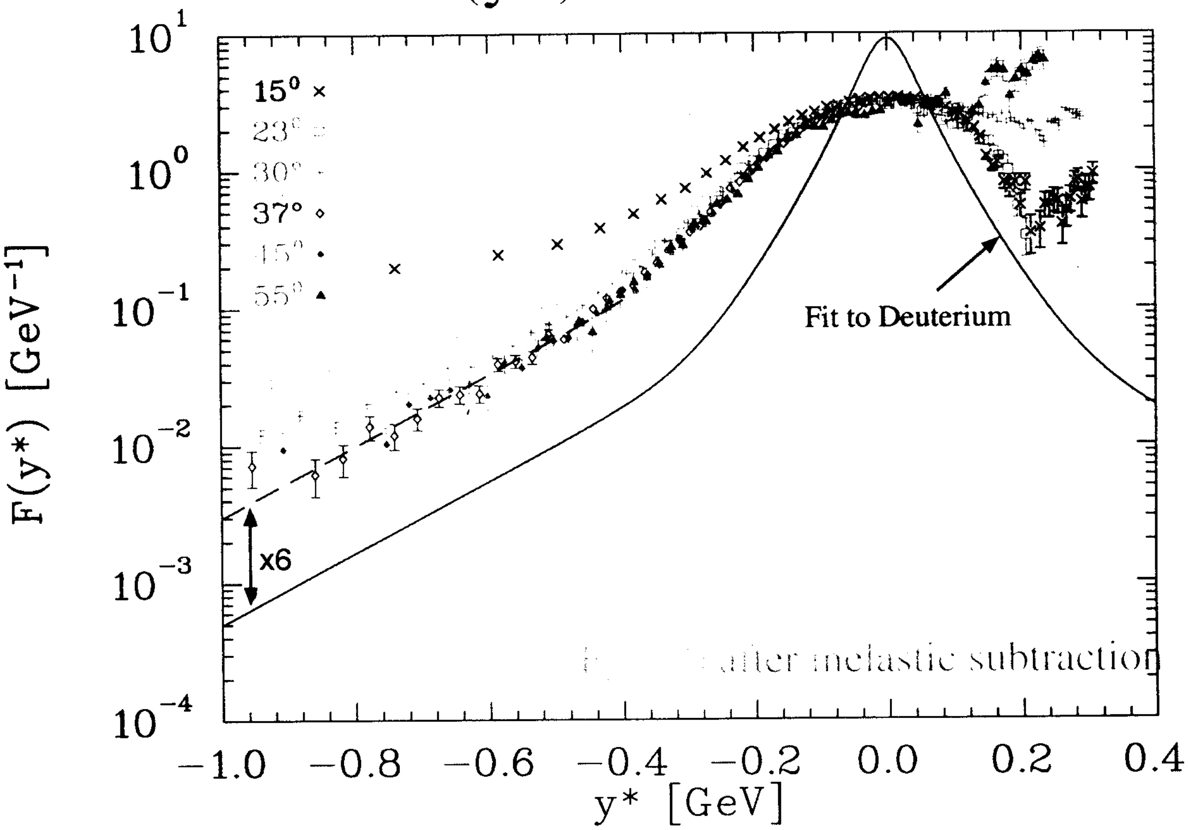


15°
37°
from total cross section
F(y) [GeV^-1]
y [GeV]

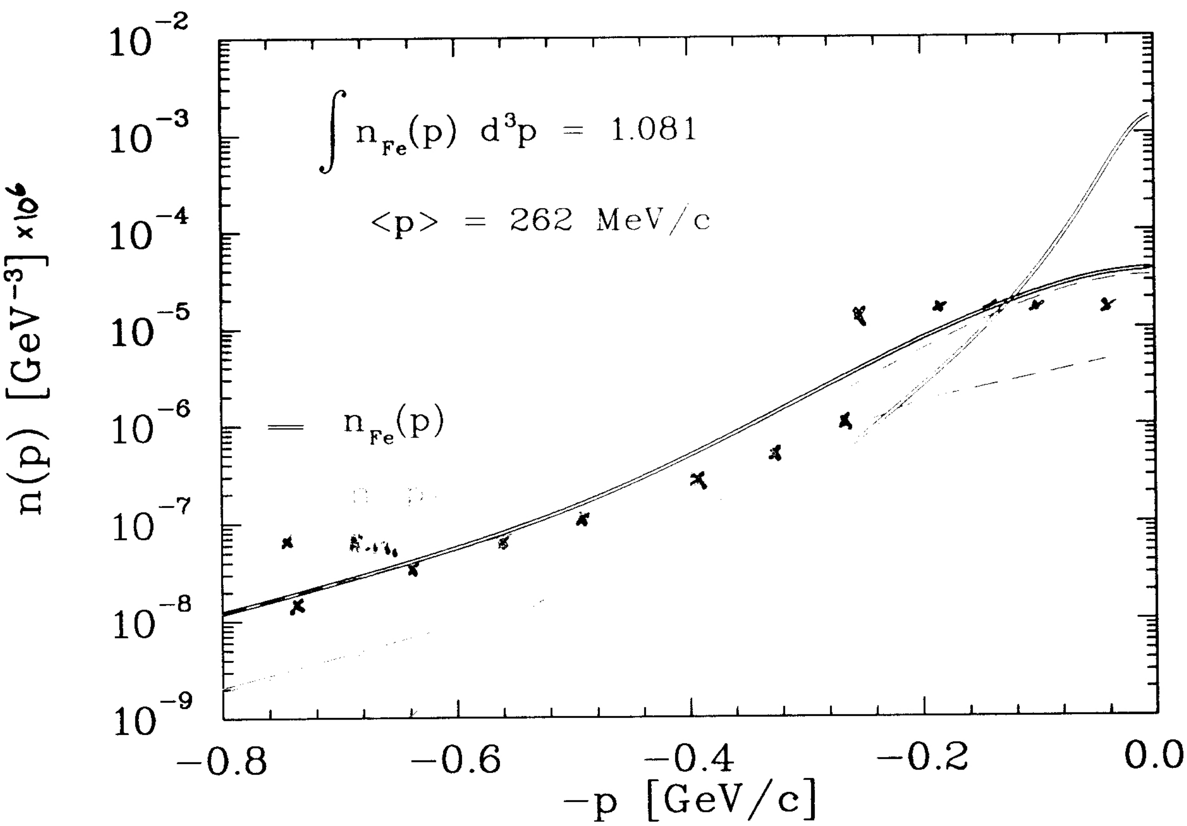


15°
37°
Fit to Deuterium
after inelastic subtraction
F(y) [GeV^-1]
y [GeV]

F(y*) for Iron



15° ×
37° ◇
Fit to Deuterium
x6
after inelastic subtraction
F(y*) [GeV^-1]
y* [GeV]



$\int n_{Fe}(p)\ d^3p = 1.081$
<p> = 262 MeV/c
$n_{Fe}(p)$
n(p) [GeV^-3] ×10^6
−p [GeV/c]

Fe from TJNAF 89-008

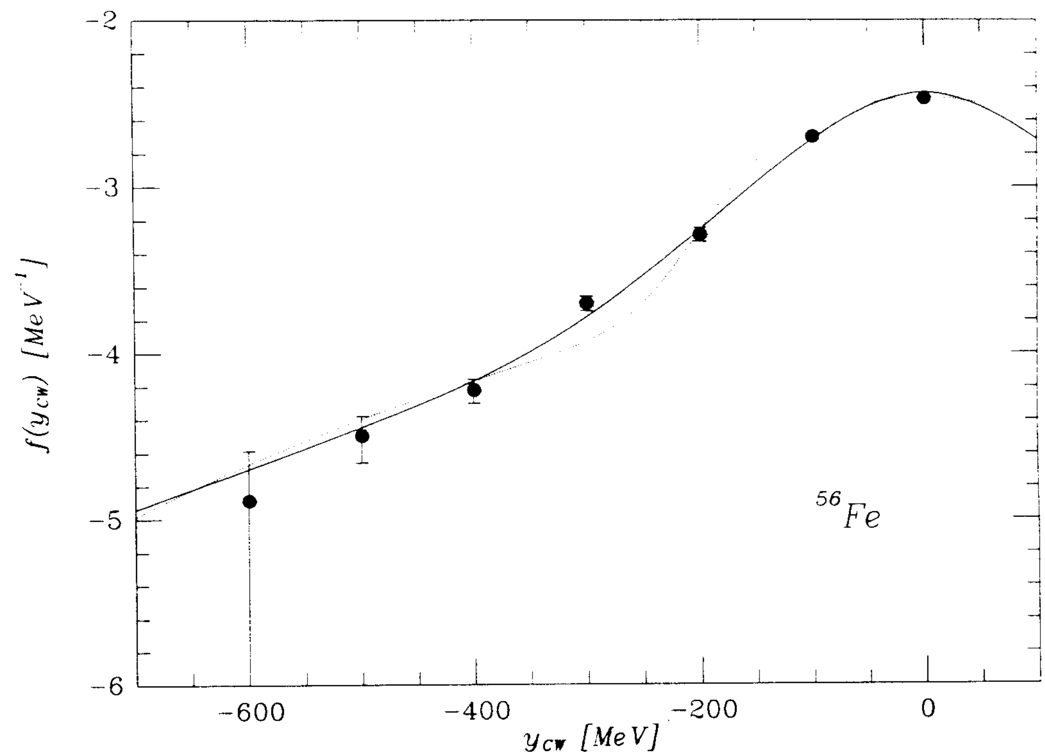
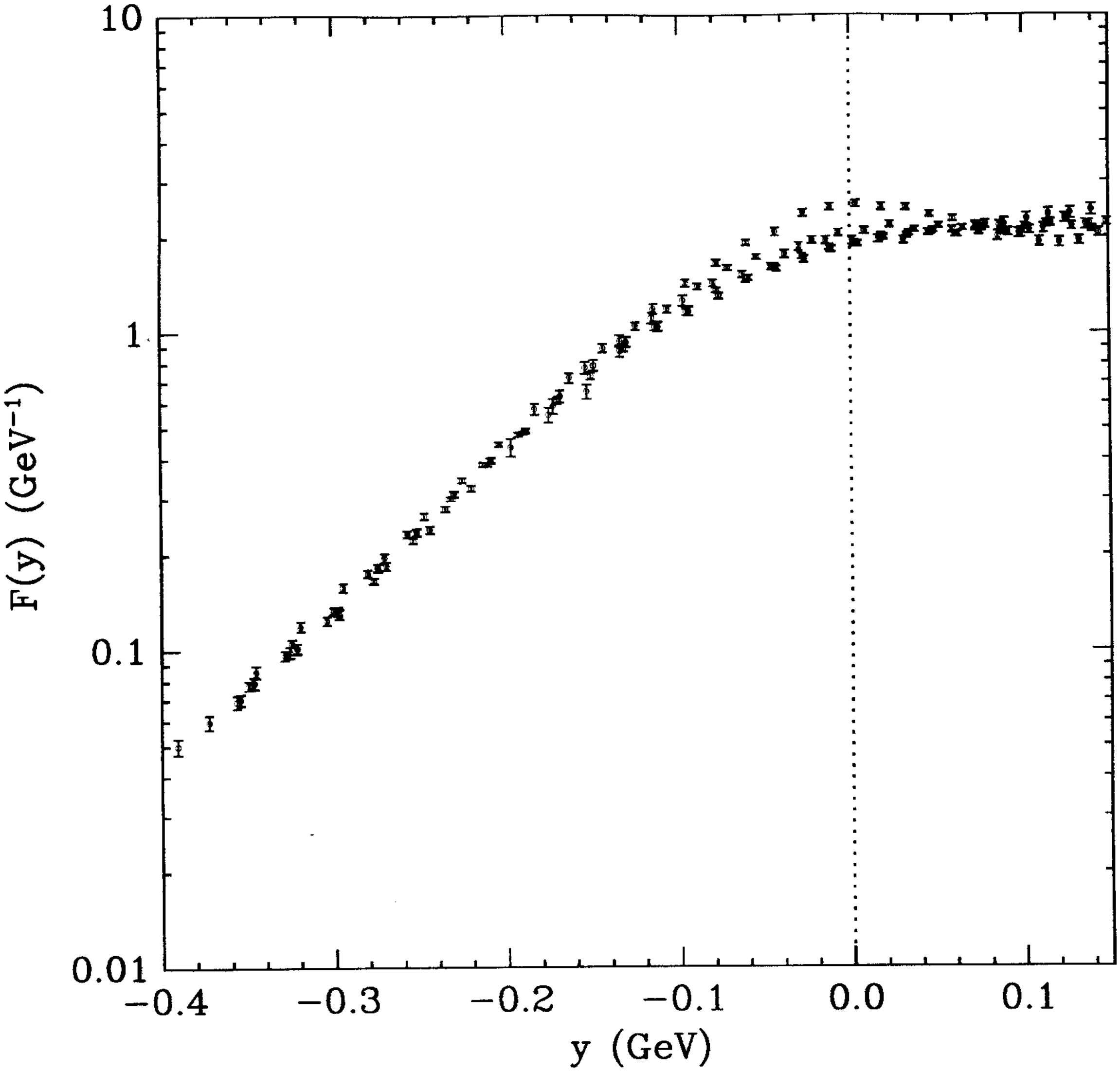


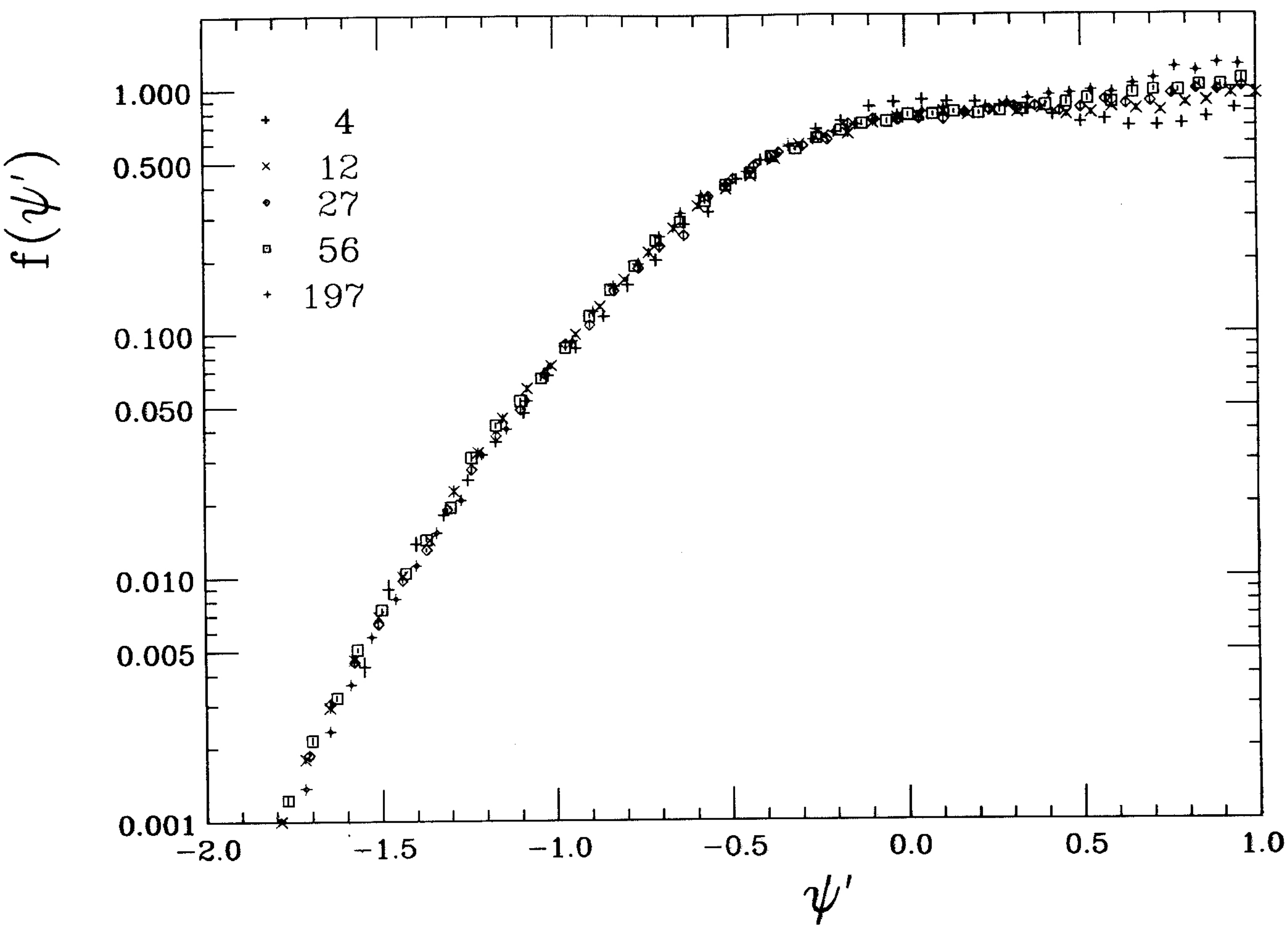
FIG. 8. The longitudinal momentum distribution (dots) for ^{56}Fe obtained from the results shown in Figs. 4-7. The dotted and solid curves correspond to two different theoretical longitudinal momentum distributions.

Faralli, Ciofi degli Atti and West

nucl-th/9910065 25 Oct 99

^{4}He, C, Al, Fe, Au 3.6, 16°





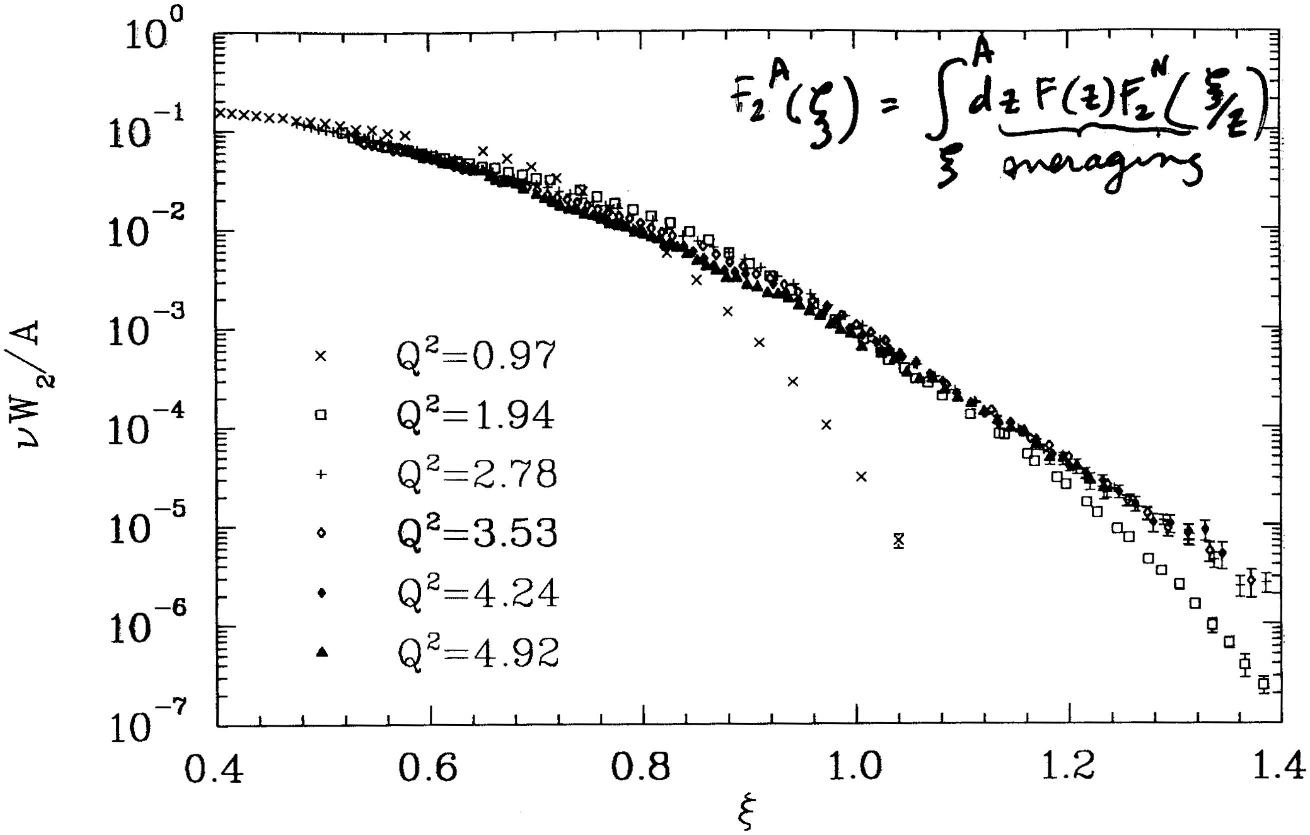
Donnelly, Sick PRL 82, 3212 (1999)

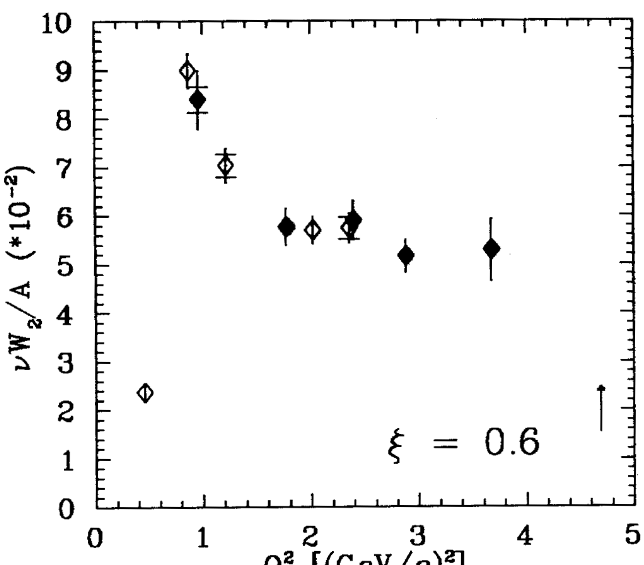
Superscaling

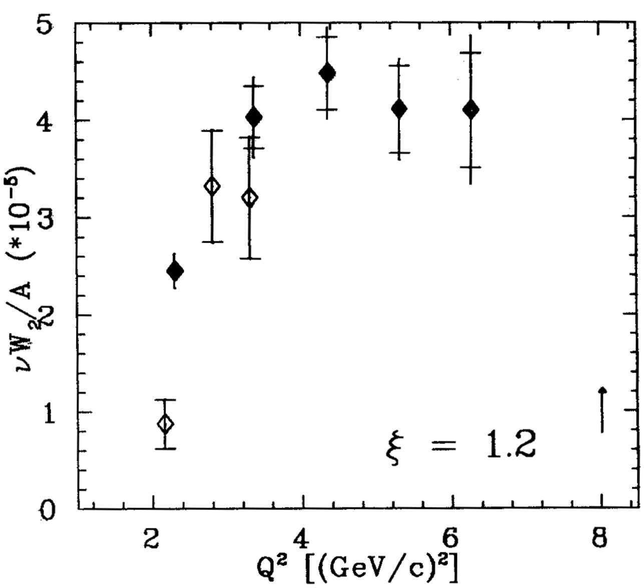
scaling of a 2nd kind

$\psi' \simeq y / k_f$

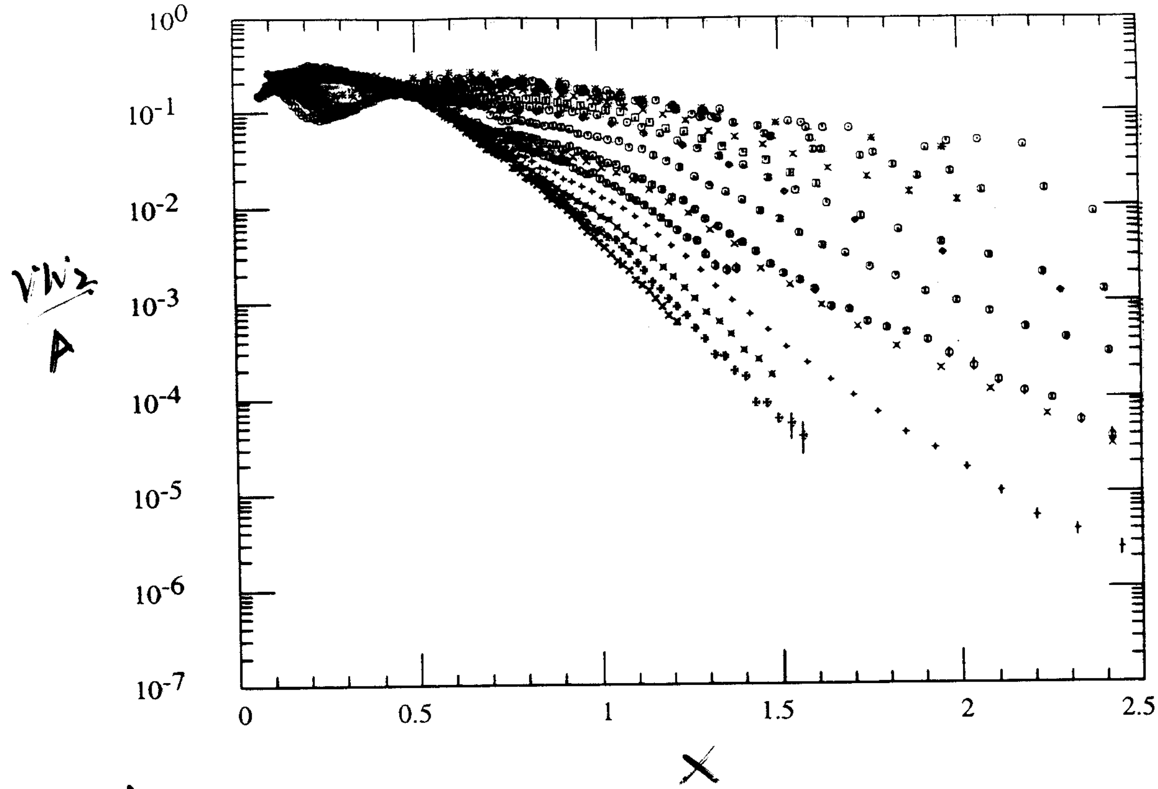
$f(\psi') = F(y) \cdot k_f$


$F_2^A(\xi) = \int_\xi^A \underbrace{dz\, F(z) F_2^N(\xi/z)}_{\text{averaging}}$
$\nu W_2/A$
ξ
$Q^2=0.97$
$Q^2=1.94$
$Q^2=2.78$
$Q^2=3.53$
$Q^2=4.24$
$Q^2=4.92$


$\nu W_2/A$ (*10^{-2})
Q^2 [(GeV/c)^2]
$\xi = 0.6$

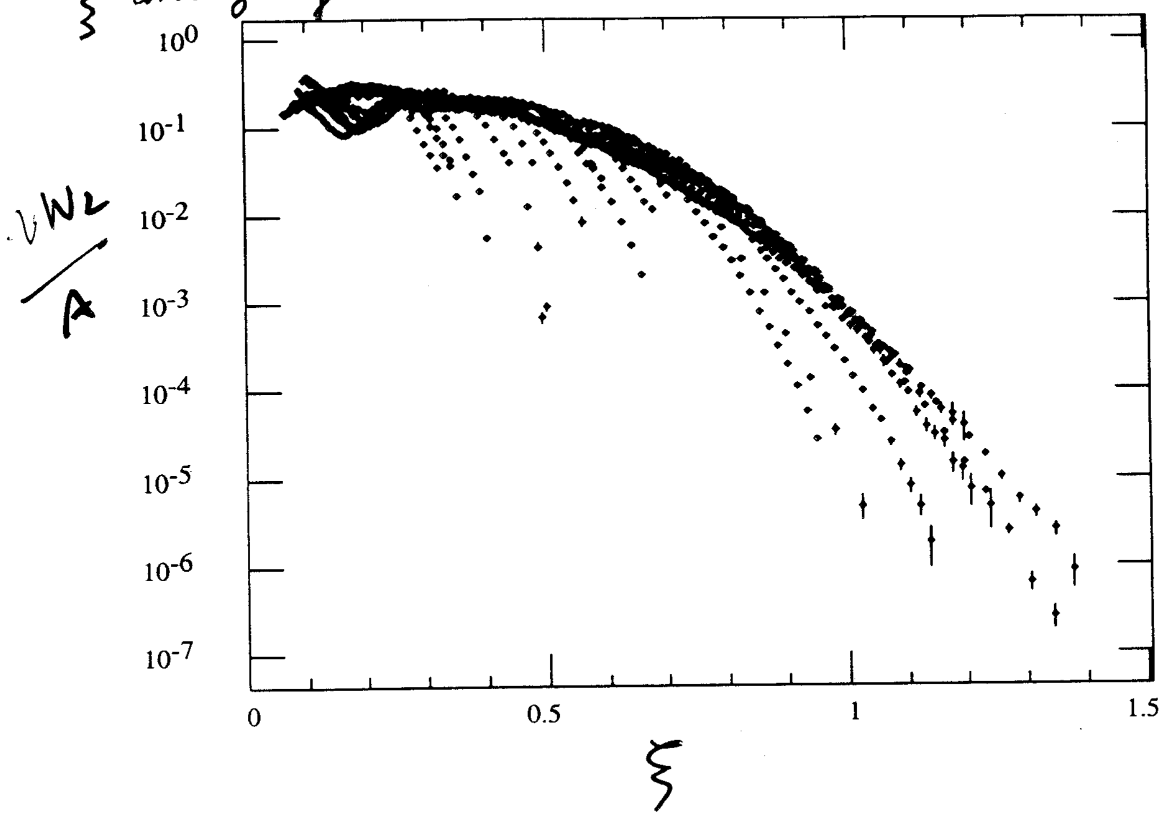

$\nu W_2/A$ (*10^{-5})
Q^2 [(GeV/c)^2]
$\xi = 1.2$

^{12}C



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

^{12}C



$$\xi = 2x \left[1 + (1 + 4m^2x^2/Q^2)^{\frac{1}{2}} \right]$$

$F_2(x) \propto e^{-sx}$

CCFR E770

CCFR E770

hep-ex/9905052 v2 30 Sep 1999

ν- Fe   ν- Fe

BCDMS μ-C

(BCDMS) μ-C

Z Phys C 63 29-36 (1994)

$$2xF_1(x,Q^2) = F_2(x,Q^2) = xF_3(x,Q^2).$$

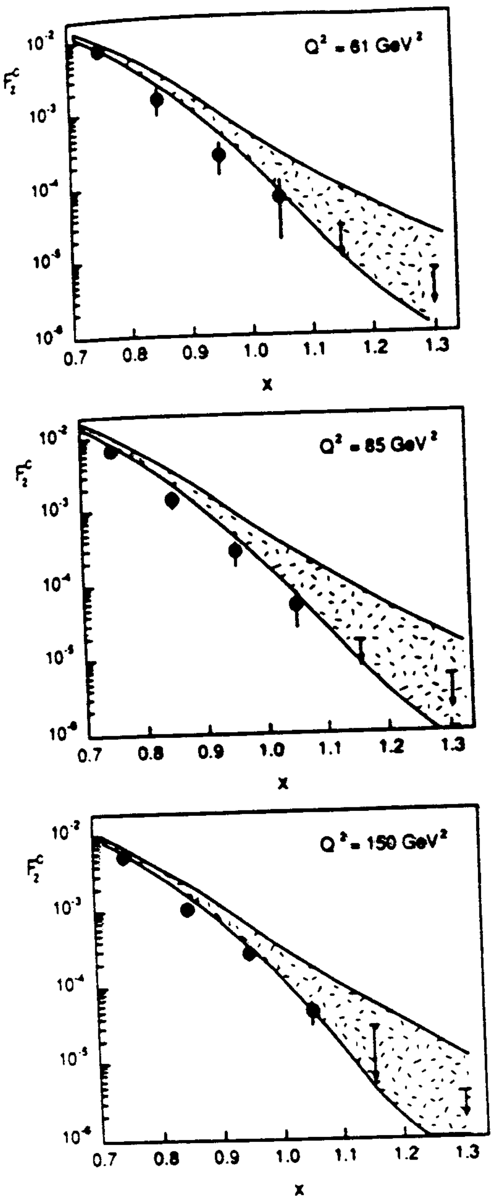


Fig. 7. The nuclear structure function $F_2^C(x)$ as a function of x, at three different values of Q^2. The hatched regions show the range of predictions of [26]

s = 16.5 ± 0.5

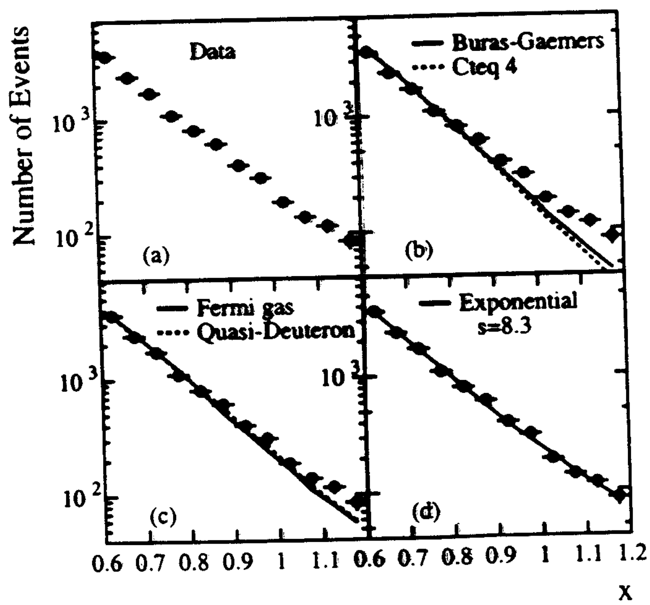


FIG. 2. (a) Measured x distribution. Comparison measured x distribution and (b) distribution predicted Buras-Gaemers structure functions and by CTEQ4M stı ture functions, (c) distributions predicted by a flat Fermi model and by the Bodek-Ritchie model, (d) distributions wı an exponentially falling F_2 with s=8.3. All error bars rep sent only the statistical errors.

89-008

C s = 17 ± 0.2

Fe s = 16.2 ± 0.2

Au s = 15.2 ± 0.5

ρ = 1

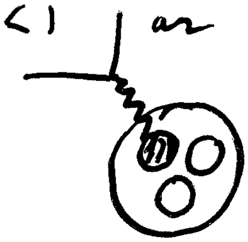
Correlations

F+S PR 160 (88)

F, S, D, Sargsyan PRC 48 2451 (93)

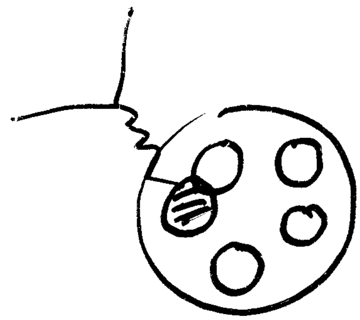
NRIA

for nucleon at rest, $x < 1$ or $x = 1$
elastic limit



Nucleon

e-A scattering



$x > j - 1$

where j is number of nucleons coming together

(Recall for k_f, $x \leq 1.2$)

$x > 1 \Rightarrow$ 2 nucleons close together

$x > 2 \Rightarrow$ 3 nucleons close together

Further when j nucleons are close together the $A-j$ nucleons have little influence

Carry further

The spectral function w/ a high k nucleon can be represented as a sum over 2, 3 nucleon correlations; one must account for CM motion of the correlation.
[Frankfurt/Strikman
C. degli Atti, Simula]

In the region where correlations should dominate, large x,

$$\sigma(x,Q^2) = \sum_{j=2}^{A} A \frac{1}{j} a_j(A)\, \sigma_j(x,Q^2)$$

$$= \frac{A}{2} a_2(A)\, \sigma_2(x,Q^2) +$$

$$\frac{A}{3} a_3(A)\, \sigma_3(x,Q^2) +$$

$$\vdots$$

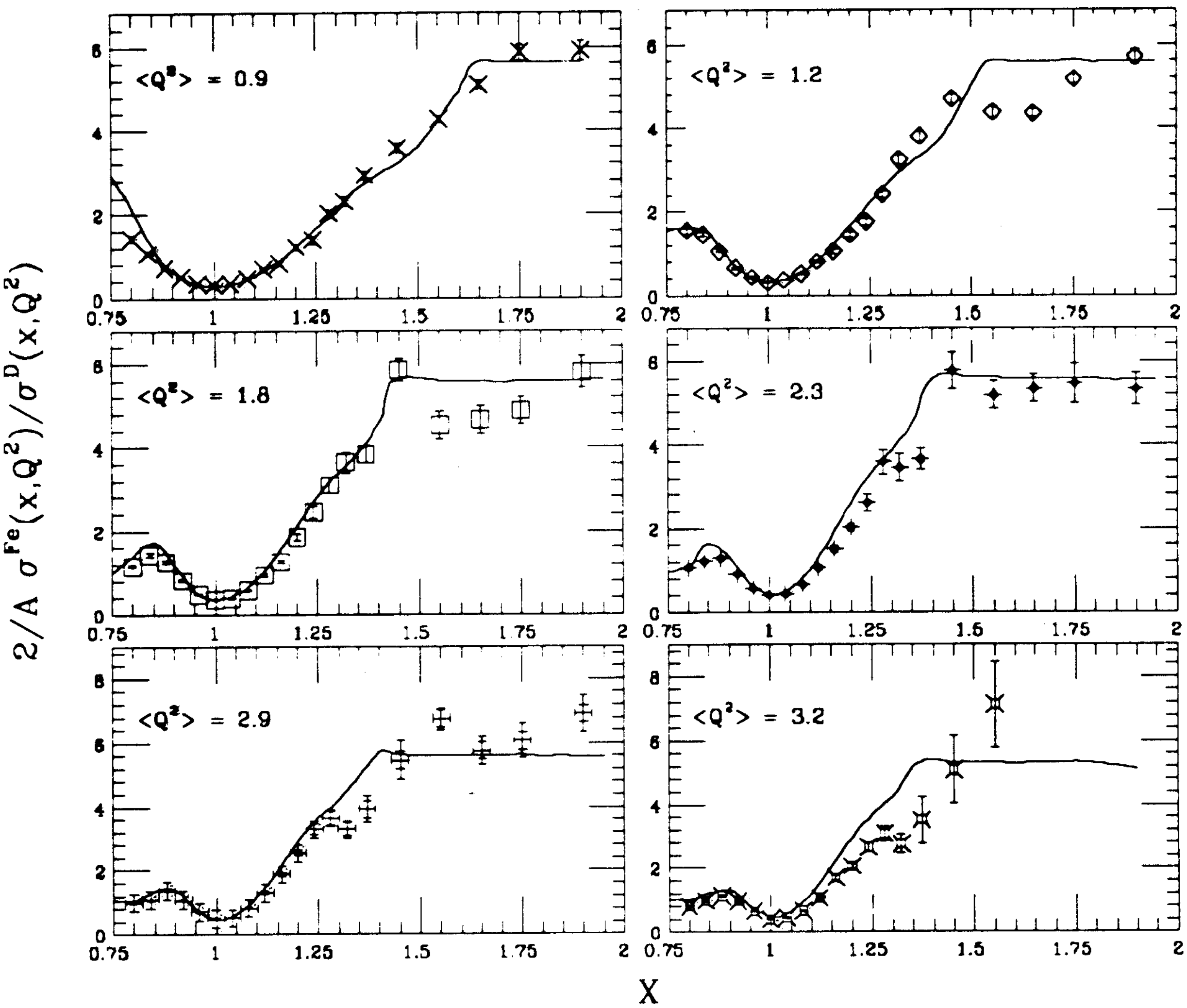
$\sigma_2(x,Q^2) = \sigma_{ep}(x,Q^2)$

Now $\underline{\underline{a_j(A)}}$ are proportional to finding a nucleon in a j-nucleon correlation. $a_j(A)$ should fall rapidly w/ j as nuclei are dilute

$\sigma_j(x,Q^2) = 0$ for $x > j$

Frankfurt
Strikman
Day, Sargsyan '93

NE3 A > 2
E101 A = 2
E133 A = 2



$$\sigma(x, Q^2) = \sum_{j=2}^{A} A \frac{1}{j} a_j(A) \sigma_j(x, Q^2)$$

for $x > j$

$$\frac{2}{A} \frac{\sigma_A}{\sigma_D} = a_2(A)$$

$a_2(A)$ prop to probability of a j-nucleon correlation

FSI

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

probability for a 2N cluster (short range correlation)

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

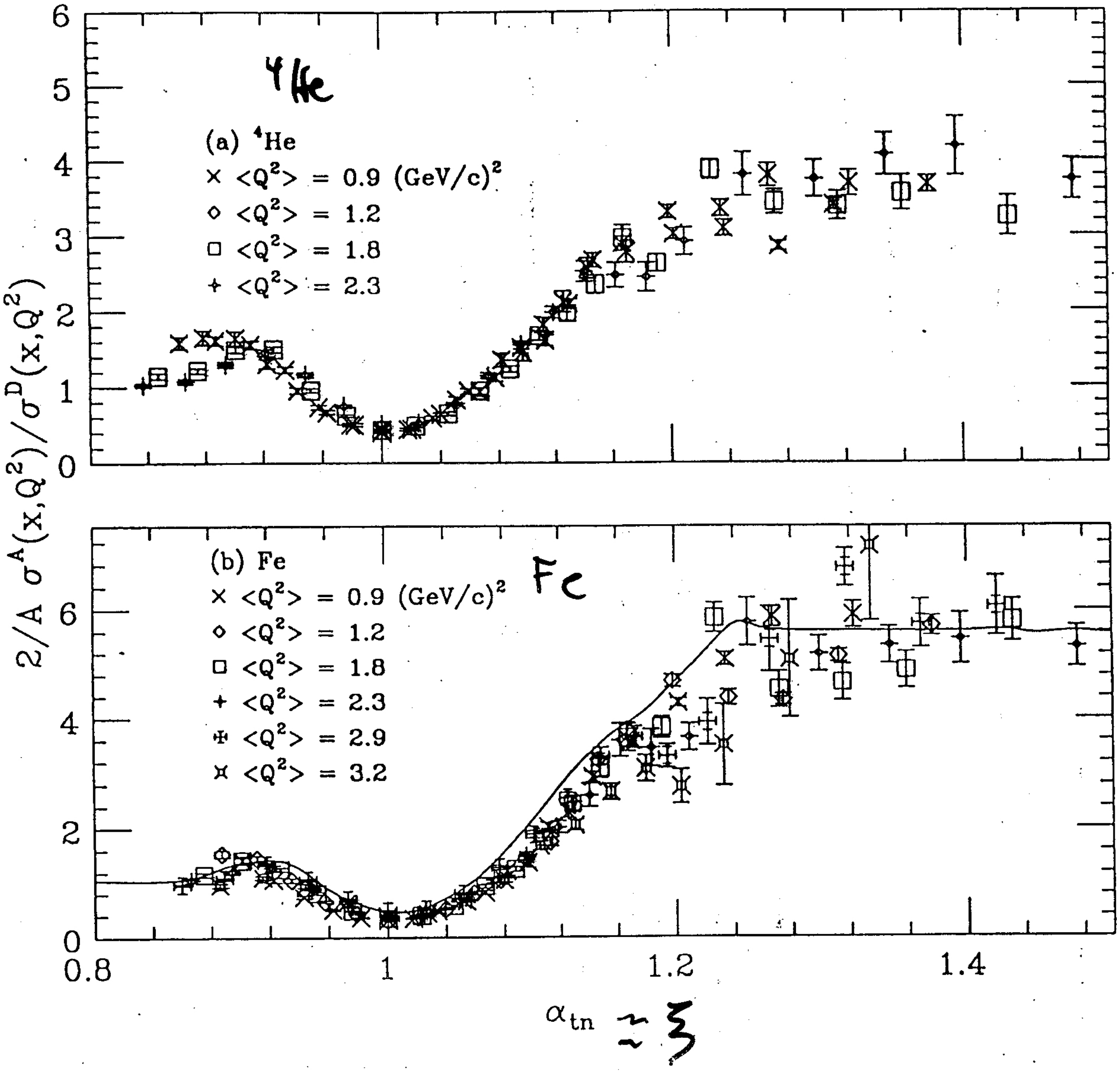
In the ratio, offshell effects and FSI largely cancel

Further a light cone presentation reveals a scaling relation

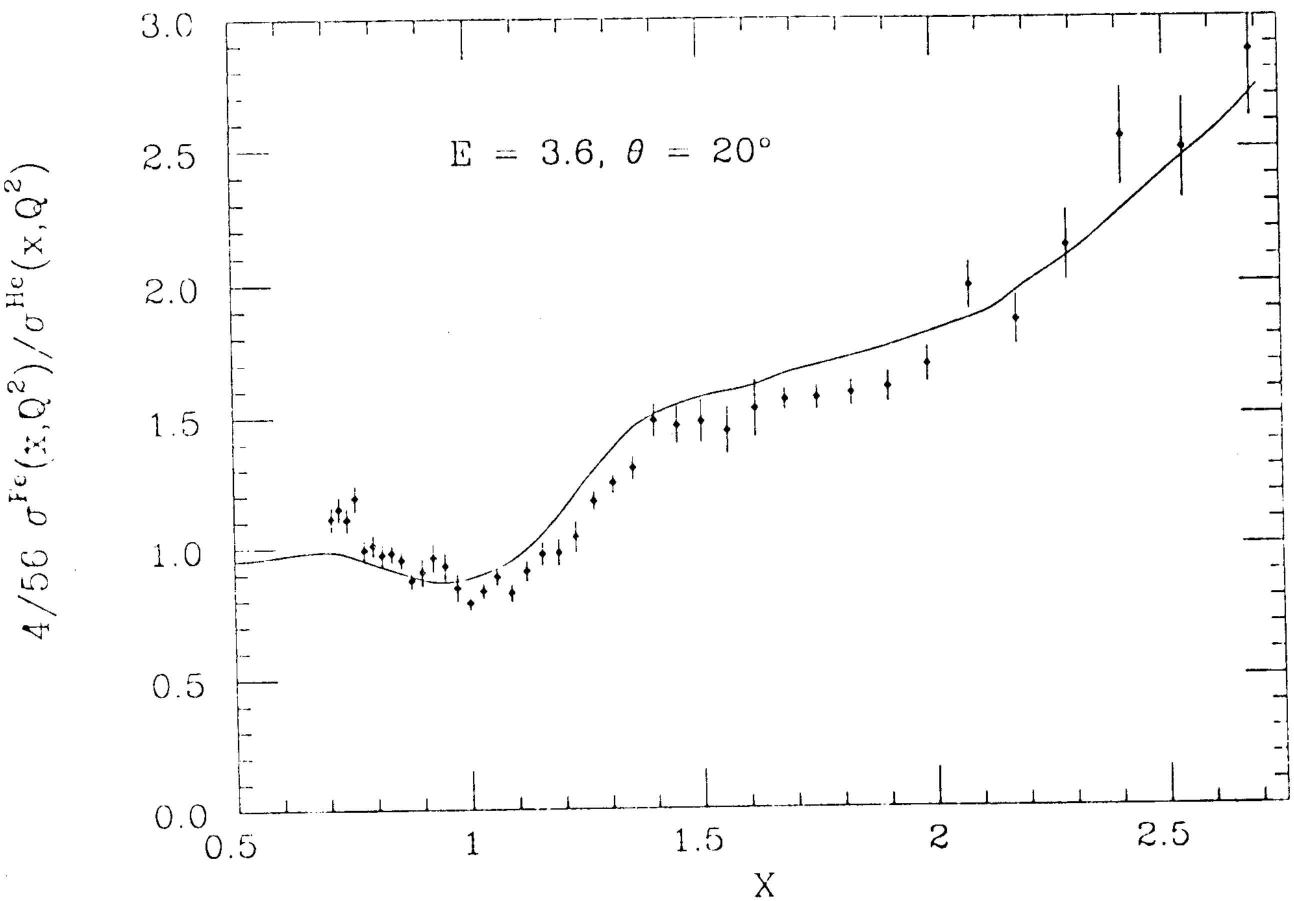
$$\frac{\sigma_{A_1}(x,Q^2)}{\sigma_{A_2}(x,Q^2)} = \frac{\int \rho_{A_1}(\alpha_{tn},p_t)\,d^2p_t}{\int \rho_{A_2}(\alpha_{tn},p_t)\,d^2p_t}$$

$\Rightarrow$ ratio function of $\alpha_{tn} \simeq \xi$ variable

Ratio of $\frac{\sigma^A}{\sigma^D}$

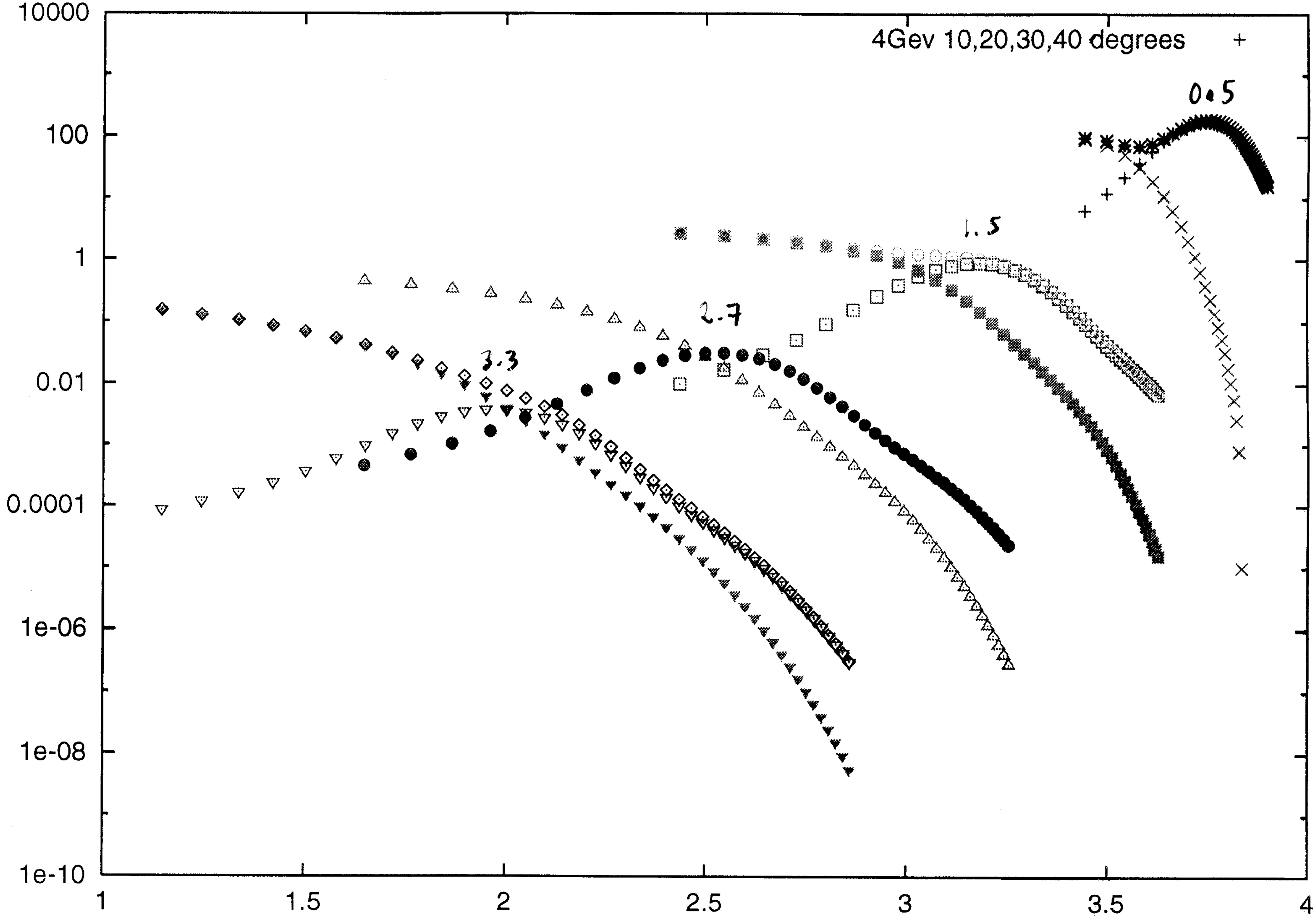


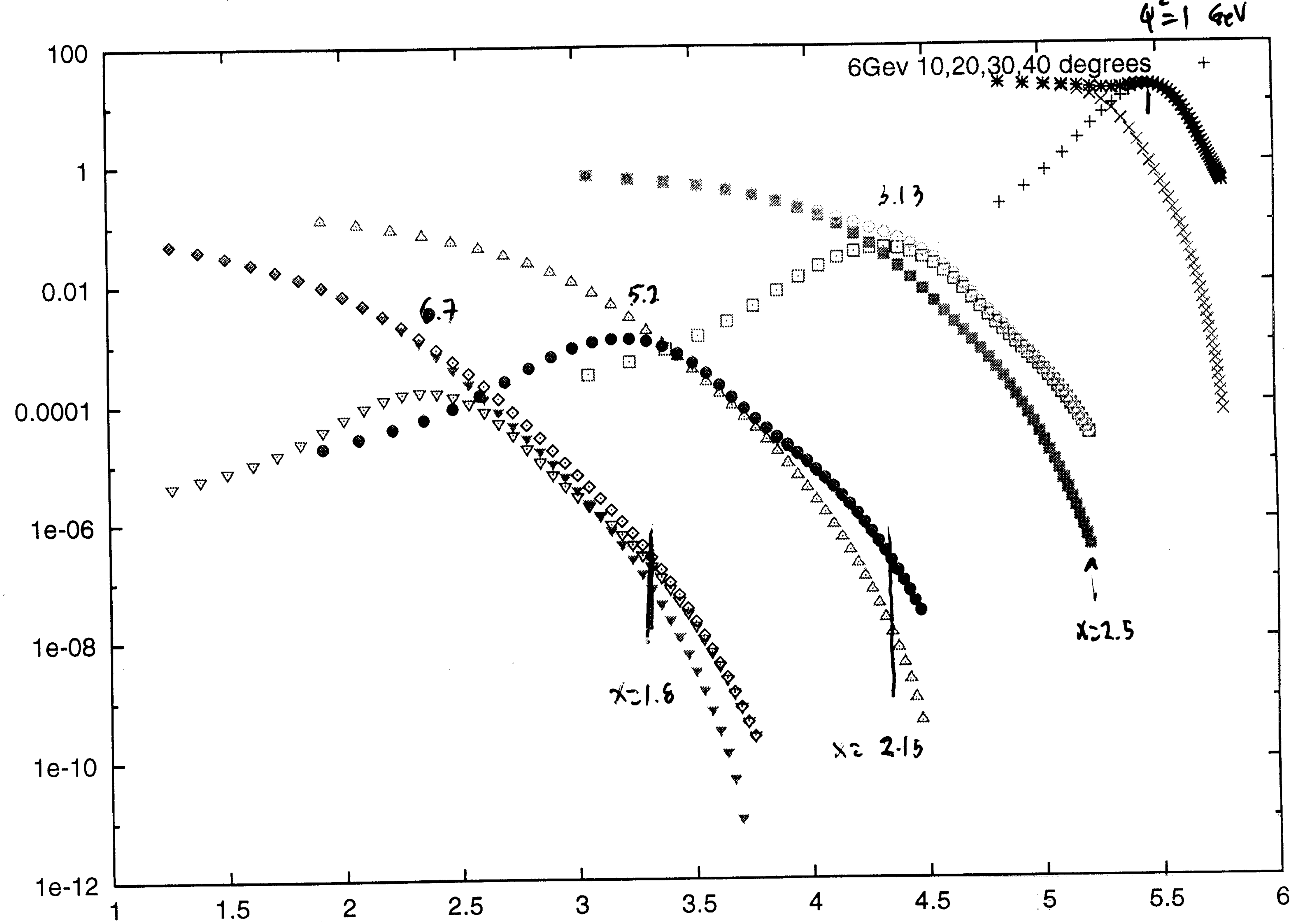
Frankfurt, Strikman, Day, Sargsian, PRC 93



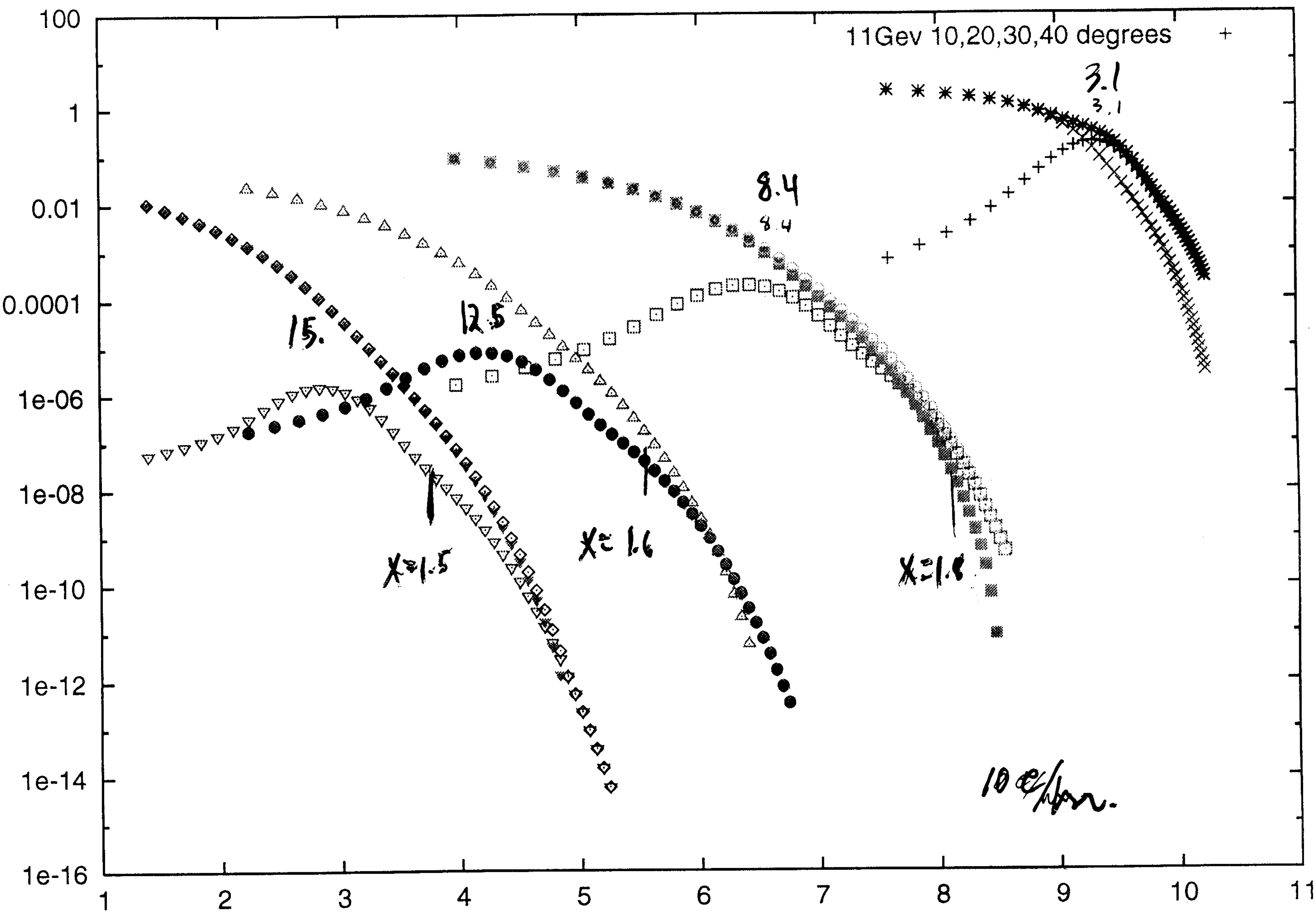
NE3 data

Quark cluster calc. J. Vary, Lecture Notes in Physics 260 (422) 1986


4Gev 10,20,30,40 degrees
0.5
1.5
2.7
3.3
10000
100
1
0.01
0.0001
1e-06
1e-08
1e-10
1
1.5
2
2.5
3
3.5
4

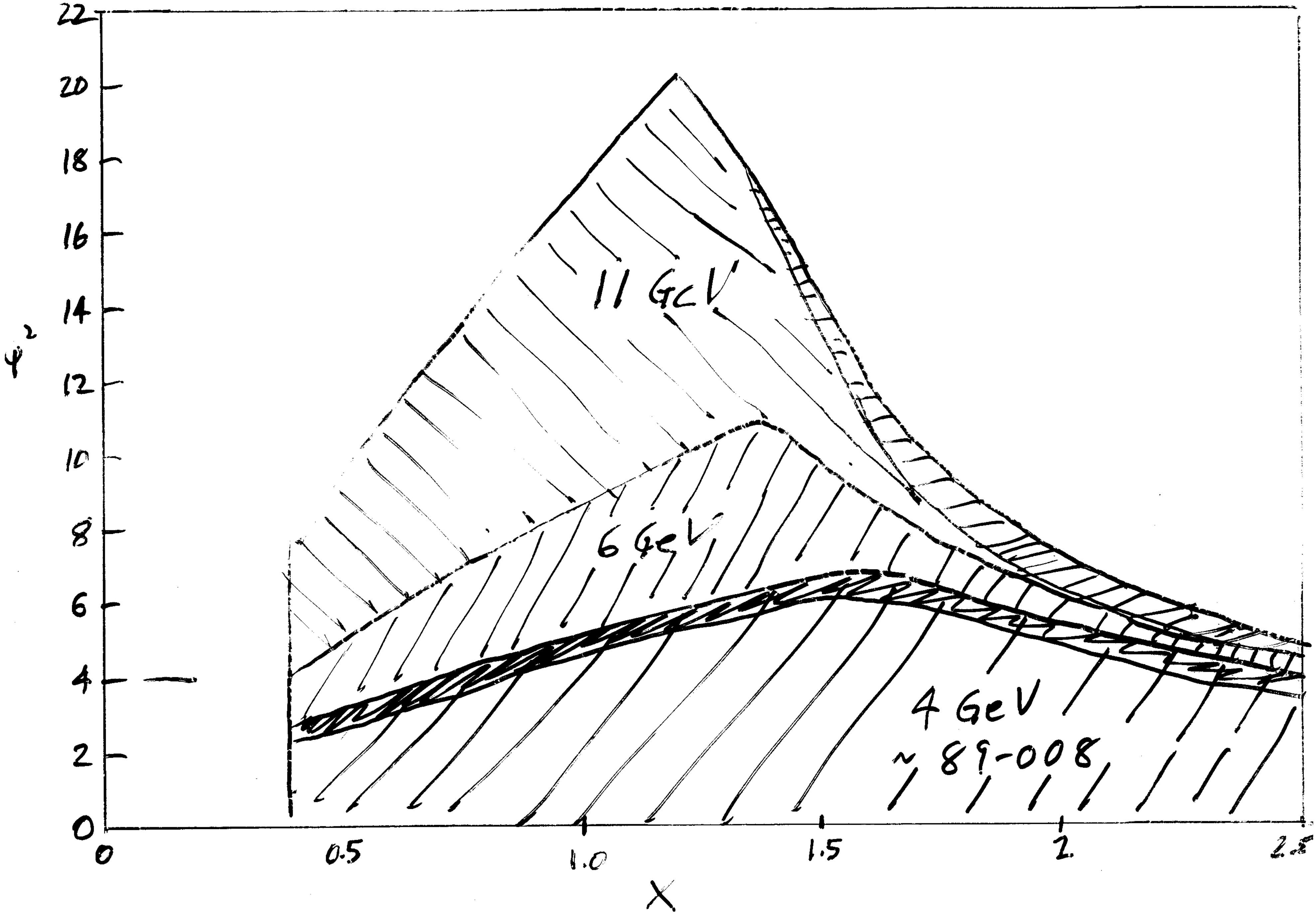


$q^2=1$ GeV^2
6Gev 10,20,30,40 degrees
3.13
5.2
6.7
x=1.8
x= 2.15
x=2.5
100
1
0.01
0.0001
1e-06
1e-08
1e-10
1e-12
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6



11Gev 10,20,30,40 degrees
3.1
3.1
8.4
8.4
15.
12.5
X=1.5
X=1.6
X=1.8
10 e/ym.
100
1
0.01
0.0001
1e-06
1e-08
1e-10
1e-12
1e-14
1e-16
1
2
3
4
5
6
7
8
9
10
11

10 events/hr in 0.015 x bin, 6% r.l Fe, 60μa, ΔΩ = 7 msr
15 cm LD_2, 100μa, ΔΩ = 7 msr



Conclusion

- $E_0 = 11$ GeV very beneficial
  - clean experiments can be done
  - extend Q^2 by a significant factor
  - DIS hard to dominate QES
- For highest Q^2 existing HMS spectrometer can be used