DEEP INELASTIC e^- and ν SCATTERING ON NUCLEI

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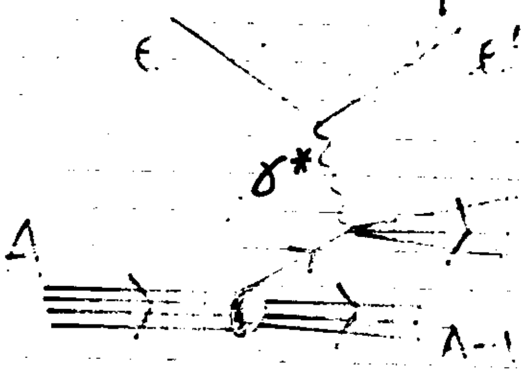
Results of calculations of the following processes :

1) Inclusive e-Nucleus Deep Inelastic Scattering



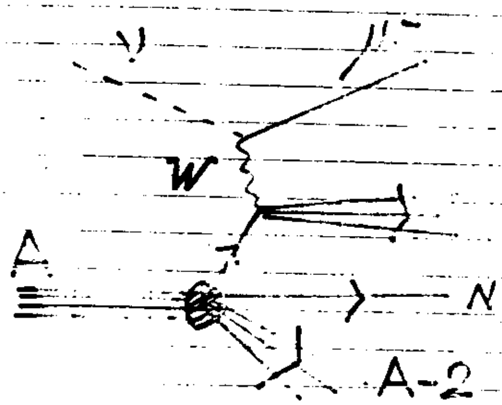
$x < 0.2$ shadowing and antishadowing
$\Rightarrow$ gluon distribution

$0.2 < x < 1$ "Binding model" of the EMC effect

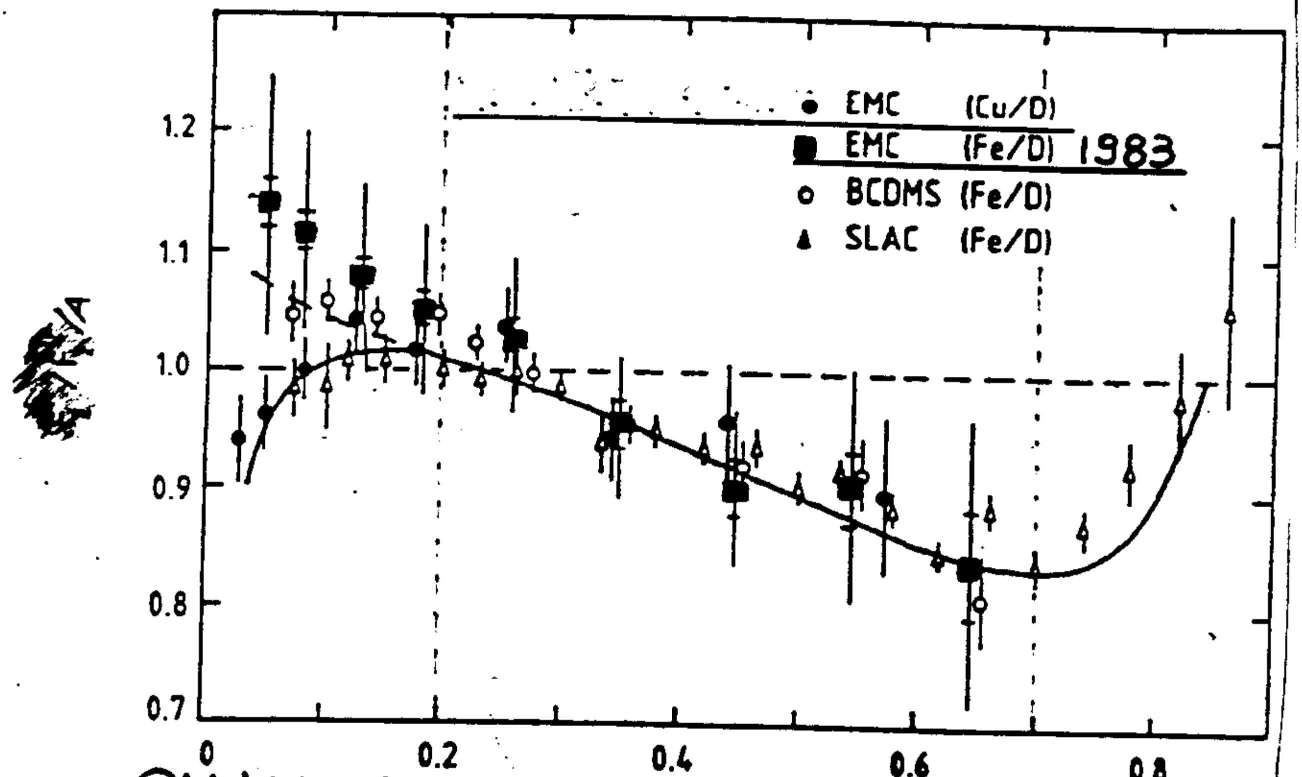
$x > 1$ Effect of NN correlations

2) Semi-inclusive ν Nucleus DIS

EFFECT of CORRELATIONS and DIQUARK FRAGMENTATION



1990



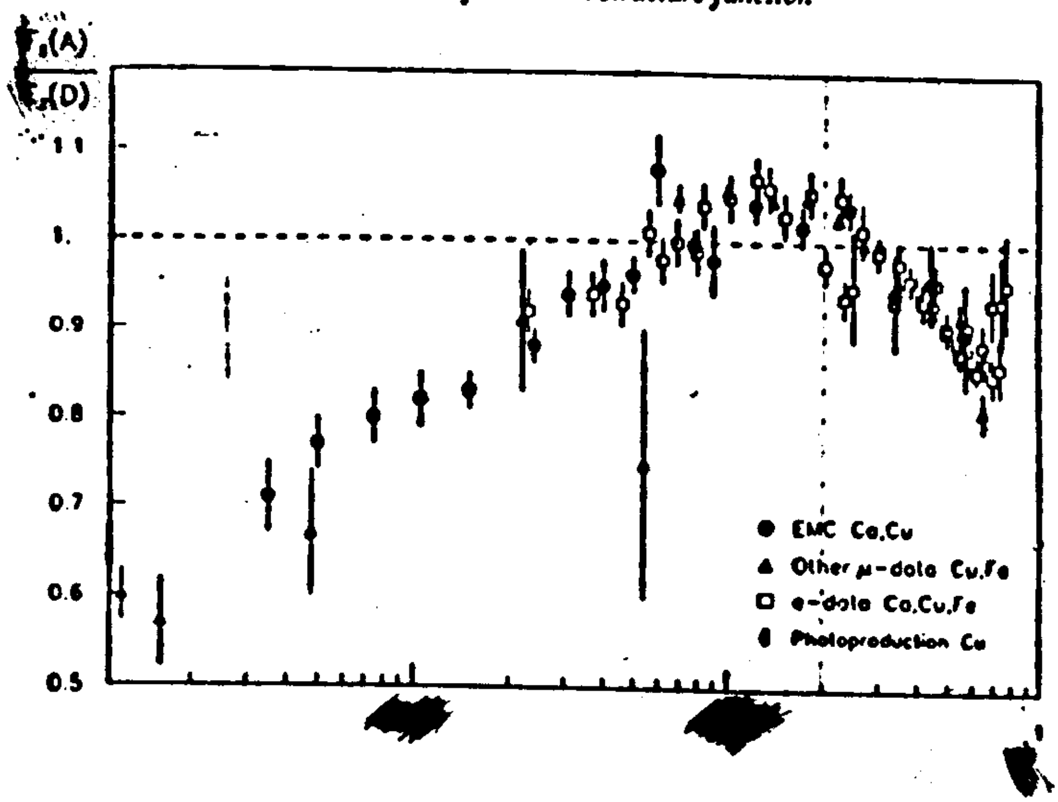
SMALL X LARGE X →

Δ $2 \leq Q^2 \leq 25$ GeV^2

o $25 \leq Q^2 \leq 200$ GeV^2

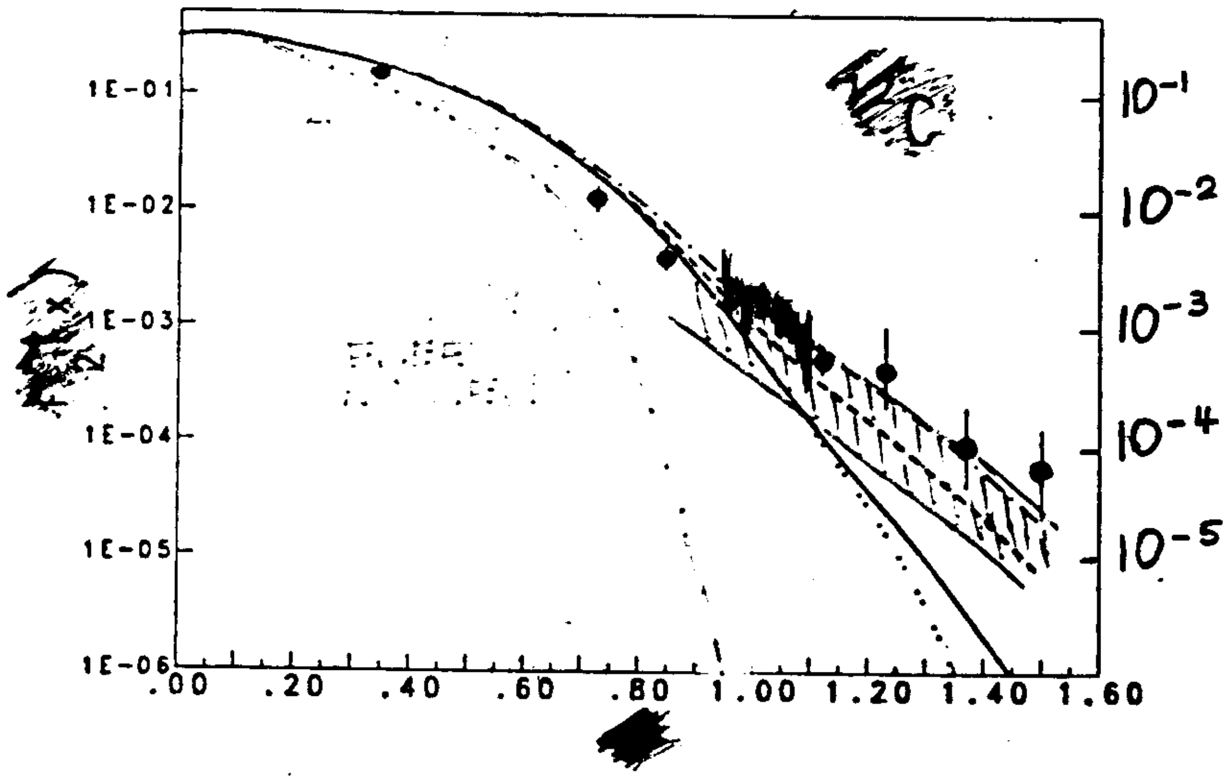
1) $F_2^A(x,Q^2)/A \simeq F_2^N(x,Q^2)$, $x < 1$

2) A consistent, unified description of the three regions is still lacking



M. ARNEODO et al. N.P. B33[illegible] (19[illegible]) [illegible]

$x \gtrsim 1$

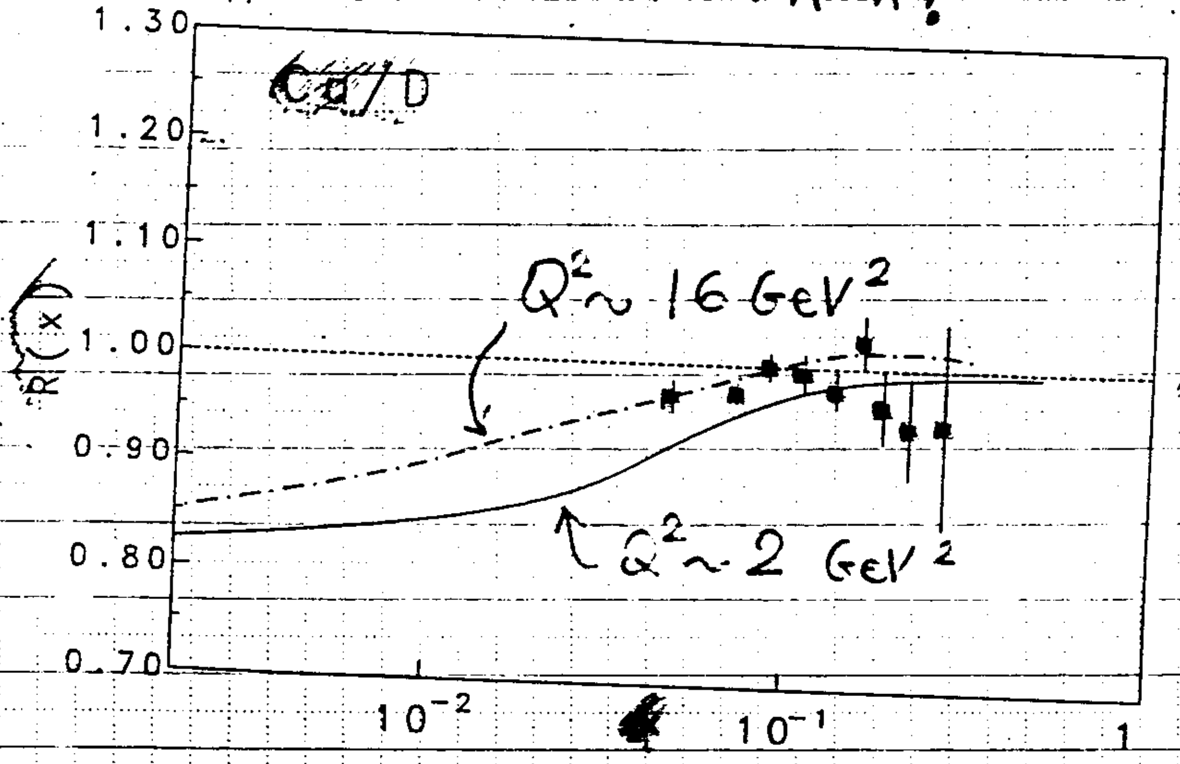


• $\langle Q^2 \rangle = 50\ \mathrm{GeV}^2$

(^{27}Al) $8 \lesssim Q^2 \lesssim 10\ \mathrm{GeV}^2$

L. Frankfurt, M. Strikman, S.L., Physical Review Letters

NEW DATA!



Experimental data : D.M. Alde et al., P.R.L. 64, 2479 (1990)

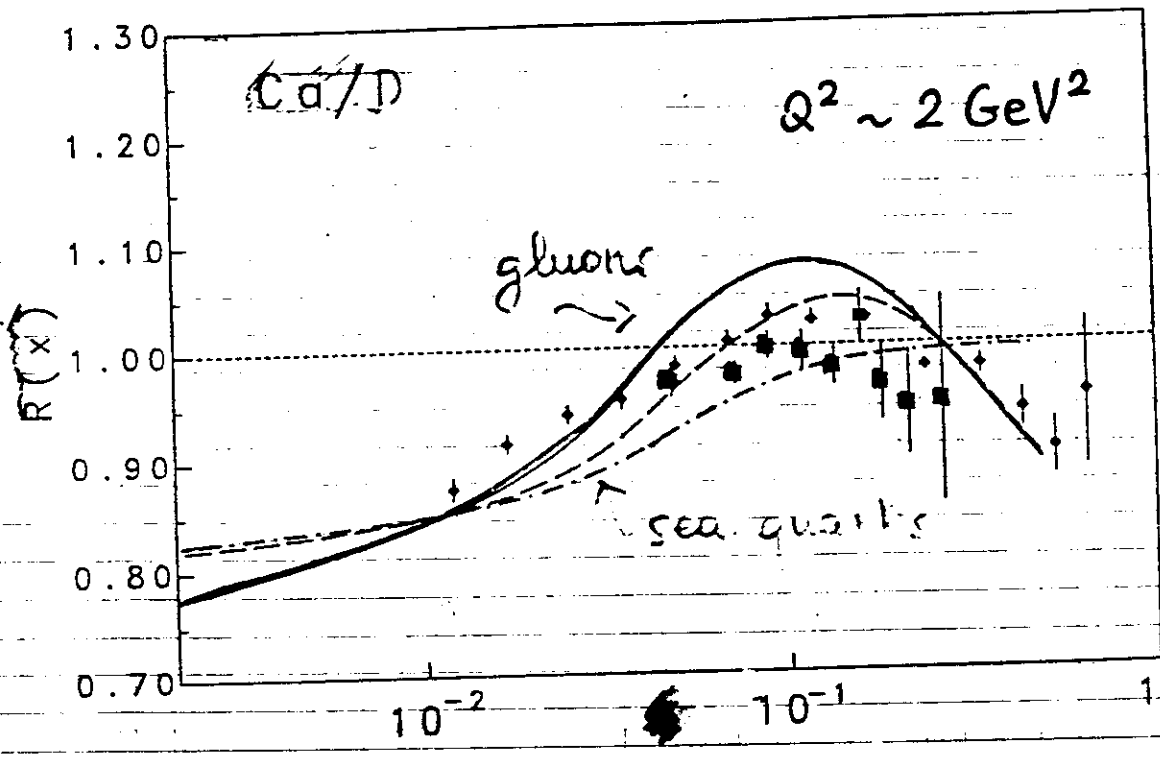
=> $\mu^+\mu^-$ production on nuclei, $Q^2 \geq 16$ GeV

- Measure directly the sea quarks ratio

=> SHOW NO NUCLEAR DEPENDENCE ABOVE $x > 0.1$

=> VERY SMALL SHADOWING AT $x < 0.1$

L. Frankfurt, M. Strikman, S.L., Physical Review Letters in press



■ D.M. Alde et al, P.R.L. 64, 2479 (1990)

◆ M. Arneodo et al., P.L.B 211, 493 (1988)

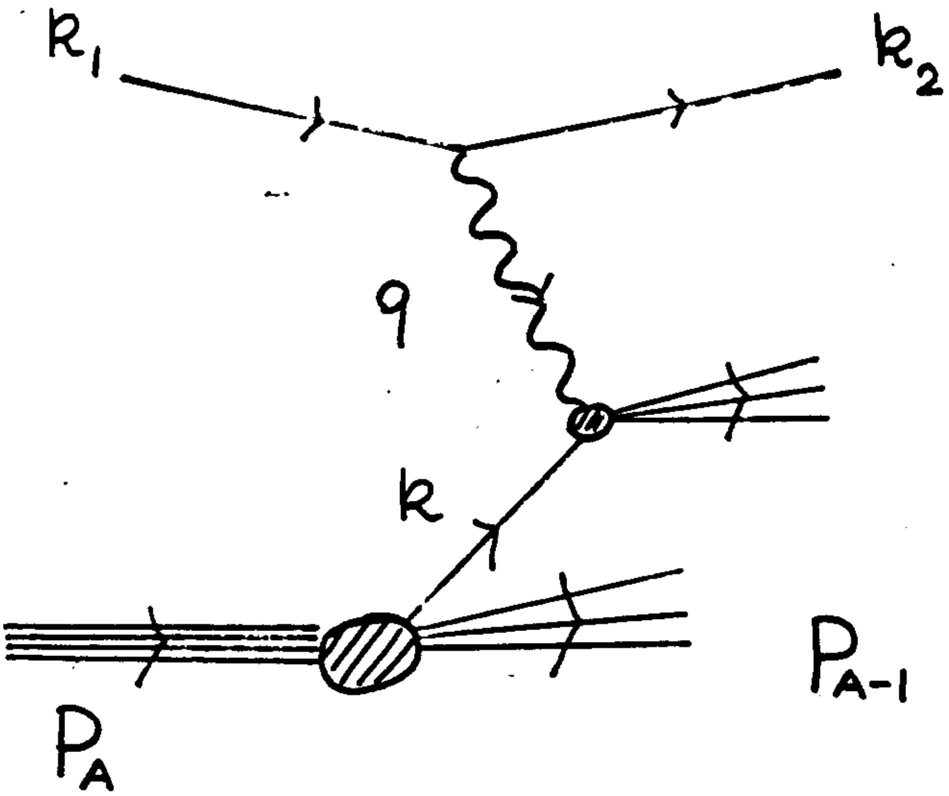
The only description which is consistent with BARYON CHARGE and MOMENTUM SUM rules

$$\int_0^1 dx\, V_N(x) = \int_0^A dx\, \frac{1}{A} V_A(x) \qquad \text{BARYON}$$

$$\int_0^1 dx\, V_N + G_N + S_N = \int_0^A dx\, \frac{1}{A}(V_A + G_A + S_A) \qquad \text{MOMENTUM}$$

$0.9 \leq X \leq 1$ "EMC"

KINEMATICS



IA

i) The nuclear hadronic tensor $W_{\mu\nu}^{(A)}$ is obtained from $\sum_{i=1}^{A} J_\mu^{(N)}$

ii) No interference terms $\to J_\mu^i J_\nu^j$, $i \neq j$

iii) No FSI

LAB

$$k_{1\mu} \equiv (\varepsilon_1, \underline{k}_1) \quad k_{2\mu} \equiv (\varepsilon_2, \underline{k}_2)$$

$$q_\mu \equiv (\nu, \underline{q}) \rightarrow q^2 = \underline{q}^2 - \nu^2 \equiv -Q^2$$

$$\begin{cases} P_A \equiv (M_A, 0) \\ P_{A-1} \equiv \left(\sqrt{M_{A-1}^{*2} + \underline{k}_{A-1}^2}, \ \underline{k}_{A-1}\right) \\ M_{A-1}^* = M_{A-1} + E_{A-1}^* \quad (E_{A-1}^* \geqslant 0) \end{cases}$$

$$\begin{cases} k \equiv \left(M_A - \sqrt{M_{A-1}^{*2} + \underline{k}^2}, \ \underline{k} \equiv -\underline{k}_{A-1}\right) \\ E = \underbrace{(M_{A-1} + M_N - M_A)}_{E_{min}} + E_{A-1}^* \end{cases}$$

$$x = \frac{Q^2}{2(P_A q)} \frac{M_A}{M_N}; \quad x' = \frac{Q^2}{2(kq)}; \quad z = \frac{x}{x'} = \frac{kq}{M_N \nu}$$

Bjorken

light cone momentum f.

Bjorken variable

$$X = \frac{Q^2}{2(P_A q)} \frac{M_A}{M_N} \Rightarrow x \in \left(0, \frac{M_A}{M_N} \simeq A\right)$$

Bjorken variable for the "bound" nucleon

$$X' = \frac{Q^2}{2(kq)} \Rightarrow$$ x' is a function of k & E !!!

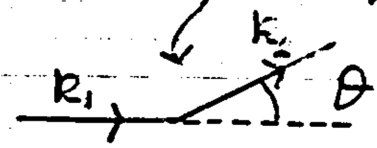
Light cone momentum fraction

$$z = \frac{X}{X'} = \frac{(kq)}{(P_A q)} \frac{M_A}{M_N} \underset{\text{BJORKEN}}{\Longrightarrow} \frac{k^+}{M_N} = \frac{(k_0 - k_3)}{M_N}$$

$$k_3 = |\underline{k}| \cos\alpha \qquad \cos\alpha = \frac{\underline{k} \cdot \underline{q}}{|\underline{k}| \cdot |\underline{q}|}$$

(e,e') cross section (Bodek & Ritchie, P.R. D23, 1 (1981))

$$\frac{d^2\sigma}{d\Omega\, d\varepsilon_2} = \sigma_M \left(W_2^A(\nu, Q^2) + W_1^A(\nu, Q^2) \cdot 2\tan^2\theta/2 \right)$$



$$W_2^A(\nu, Q^2) = \int d^3\underset{\sim}{k}\; n(\underset{\sim}{k}) \left(\frac{x}{x'}\right) \mathcal{F} \cdot W_2^N(\nu', Q^2, k^2)$$

$$W_1^A(\nu, Q^2) = \int d^3\underset{\sim}{k}\; n(\underset{\sim}{k}) \left[W_1^N(\nu', Q^2, k^2) + \frac{k_x^2}{2M_N^2} W_2^N(\nu', Q^2, k^2) \right]$$

$n(\underset{\sim}{k})$: nucleon momentum distribution

IMPROVE B.R. DESCRIPTION:

$$\int d^3\underset{\sim}{k}\; n(\underset{\sim}{k}) \longrightarrow \int d^4k \; S(k)$$

↑ NUCLEAR VERTEX FUNCTION

→ Disregard the "dynamical" off-shellness (k^2)

2) Perform the Bjorken limit: $Q^2 \to \infty$, $\nu \to \infty$, x FIXED

⇒ $\mathcal{F} \to 1$

⇒ $W_2^N = \nu F_2^N$ → $F_2^N = 2x F_1^N$

3) Describe the nucleus within a NON-RELATIVISTIC picture

→ $S(k) \sim P(\underset{\sim}{k}, E)\left(1 + O(k^2/M_N^2) + \dots\right)$

$$\boxed{F_2^A(x,Q^2) = \int d^4k\, P(\underset{\sim}{k},E)\, z\, F_2^N(x',Q^2)}$$

↓ CHANGE THE INTEGRATION VARIABLES:

$2\pi\, dk_0\, dk\, k^2\, d(\cos\alpha) \to 2\pi\, dE\, dk\, k\, dz$

↓

$$F_2^A(x,Q^2) = \int_x^A dz\, f(z)\, F_2^N\left(\frac{x}{z}, Q^2\right)$$

"The "CONVOLUTION FORMULA"

The light cone momentum distribution

$$f(z) = 2\pi M_N C_N\, z \int_{E_{min}} dE \int_{k_{min}(z,E)} dk\, k\, P(k,E)$$

$$z = \frac{x'}{x} = \frac{(kq)}{M_N \nu} = \frac{k_0\nu - k_{\parallel}|q|}{M_N\nu} \xrightarrow[\text{Bjorken}]{} \frac{k_0 - k_{\parallel}}{M_N} = \frac{k}{M}$$

1) Normalization : $\int dz\, f(z) = 1$

as for the "flux factor" problem see e.g:

L. Frankfurt & M. Strikman, P.L. B183, 254 (1987

V. Anisovitch et al., Sov. J. Nucl. Phys. 45, 1014 (198

H. Jung & G. Miller, P.L. B200, 351 (1988)

2) $f(z)$ is very nicely related to the y-scaling function $F(y,|q|)$ in the asymptotic limit !

$$F(y,|\underline{q}|) = 2\pi \int_{E_{min}}^{E_{MAX}} dE \int_{k_{min}(\nu(y),|\underline{q}|,E)}^{k_{MAX}(\nu(y),|\underline{q}|,E)} dk\, k\, P(k,E)$$

$$\nu(y) = E_{min} - M_N + \sqrt{M_N^2 + (y + |\underline{q}|)^2} \qquad (A \to \infty)$$

$$\boxed{\begin{aligned} F(y,|\underline{q}|) = \int_{E_{min}} dE \int_0^{\infty} dk\, k^2 P(k,E) \int_{-1}^{+1} d(\cos\alpha)\, \cdot \\ \cdot\, \delta\left(\nu(y) + M_N - E_{min} - \sqrt{M_N^2 + (y+q)^2}\right) \end{aligned}}$$

In the ASYMPTOTIC limit ($|\underline{q}| \to \infty$, y fixed):

$$\delta \longrightarrow \delta\left(y - \underline{k}\cos\alpha - (E - E_{min})\right)$$
$$\equiv$$
$$\delta\left(y - k^+ - (M_N - E_{min})\right)$$

$F(y,|\underline{q}|)\Big|_{q\to\infty}$ $\underline{\text{is}}$, a part from a constant shift, the l.c.m.d. !

$$\begin{cases} y = M_N(1-z) - E_{min} & (A \to \infty) \\[2ex] y = \dfrac{1}{2}\, \dfrac{(M_A - M_N z)^2 - M_{A-1}^2}{M_A - M_N z} \end{cases}$$

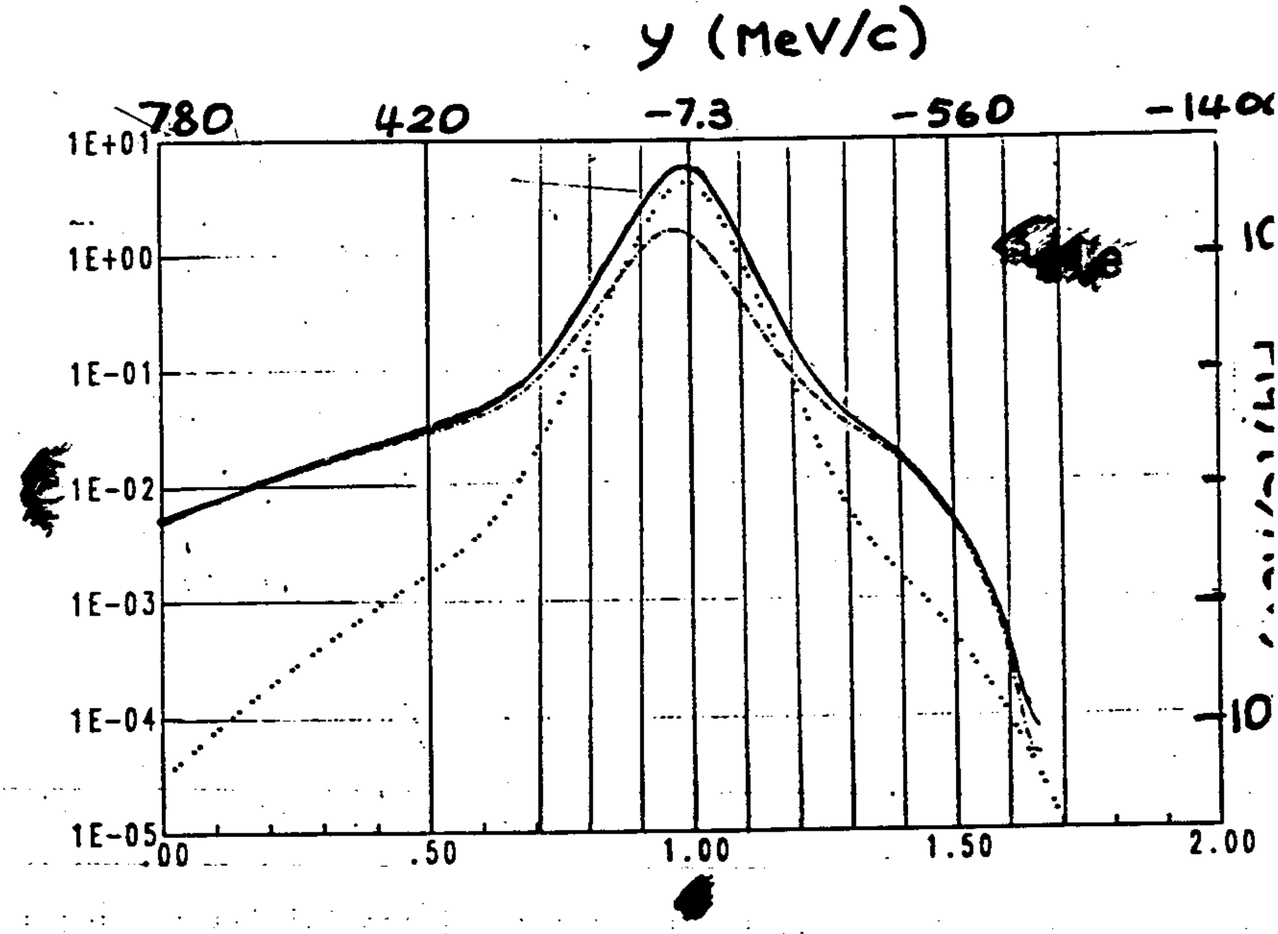


Fig. 3

·· ground	---- excited	—— total

$|\underline{q}| \to \infty$ y fixed

$$y = \frac{1}{2}\,\frac{(M_A - M_N z)^2 - M_{A-1}^2}{M_A - M_N z}$$

[redacted]

The nucleon spectral function

$$P(\underset{\sim}{k}, E) = \langle \Psi_A | a^+(k)\, \delta(E - (\hat{H}_{A-1} - E_A))\, a(k) | \Psi_A \rangle$$

$$= \sum_f |\langle \Psi_{A-1}^f | a(k) | \Psi_A \rangle|^2 \delta(E - (E_{A-1}^f - E_A))$$

$$P(\underset{\sim}{k}, E) = P_0(\underset{\sim}{k}, E) + P_1(\underset{\sim}{k}, E)$$

- $P_0(\underset{\sim}{k}, E) = \sum_\alpha \tilde{n}_\alpha(\underset{\sim}{k})\, \delta(E - |\varepsilon_\alpha|)$
- $P_1(\underset{\sim}{k}, E) = n_1(\underset{\sim}{k})\, w(\underset{\sim}{k}, E)$

$\Rightarrow \int d^3\underset{\sim}{k}\, dE\, P_0(\underset{\sim}{k}, E) = S_0 < 1$

– DEPLETION OF THE NUMBER OF NUCLEONS BELOW THE FERMI LEVEL

In mean field theories : $P_1 = 0$

and $\int d^3\underset{\sim}{k}\, dE\, P_0(\underset{\sim}{k}, E) = 1$

$0.2 \lesssim x \lesssim 0.7$

$$\boxed{F_2^A(x,Q^2) \simeq F_2^N(x,Q^2) + C_A\, x\left(\frac{\partial F_2^N}{\partial z}\right)_{z=x}}$$

$$C_A = \left[\langle E\rangle - \frac{2}{3}\langle T\rangle\right]/M_N$$

<u>SLOPE</u> $\sim C_A - C_D$

$\rightarrow \left(\langle E\rangle - E_D\right) - \frac{2}{3}\left(\langle T\rangle - \langle T\rangle_D\right)$

DEUTERON

$E_D = 2.23$ MeV

$\langle T_D\rangle = 11.5$ MeV

NUCLEUS A

$\langle E\rangle_{HF} \sim 25$ MeV $\quad \langle E\rangle_{SRC} \sim 50$ MeV

$\langle T\rangle_{HF} \sim 17$ MeV $\quad \langle T\rangle_{SRC} \sim 36$ MeV

		[redacted] (MeV)	[redacted] (MeV)	[redacted]	[redacted]	$\bar{E}_1$ (MeV)
^{12}C	[redacted]	17.0	23.0	1.0	0.0	0
	[redacted]	37.0	49.0	0.8	0.2	153.0
^{40}Ca	[redacted]	16.5	26.6	1.0	0.0	0
	[redacted]	36.0	52.1	0.8	0.2	154.0
^{56}Fe	[redacted]	17.0	25.0	1.0	0.0	0
	[redacted]	33.0	49.8	0.8	0.2	149.0

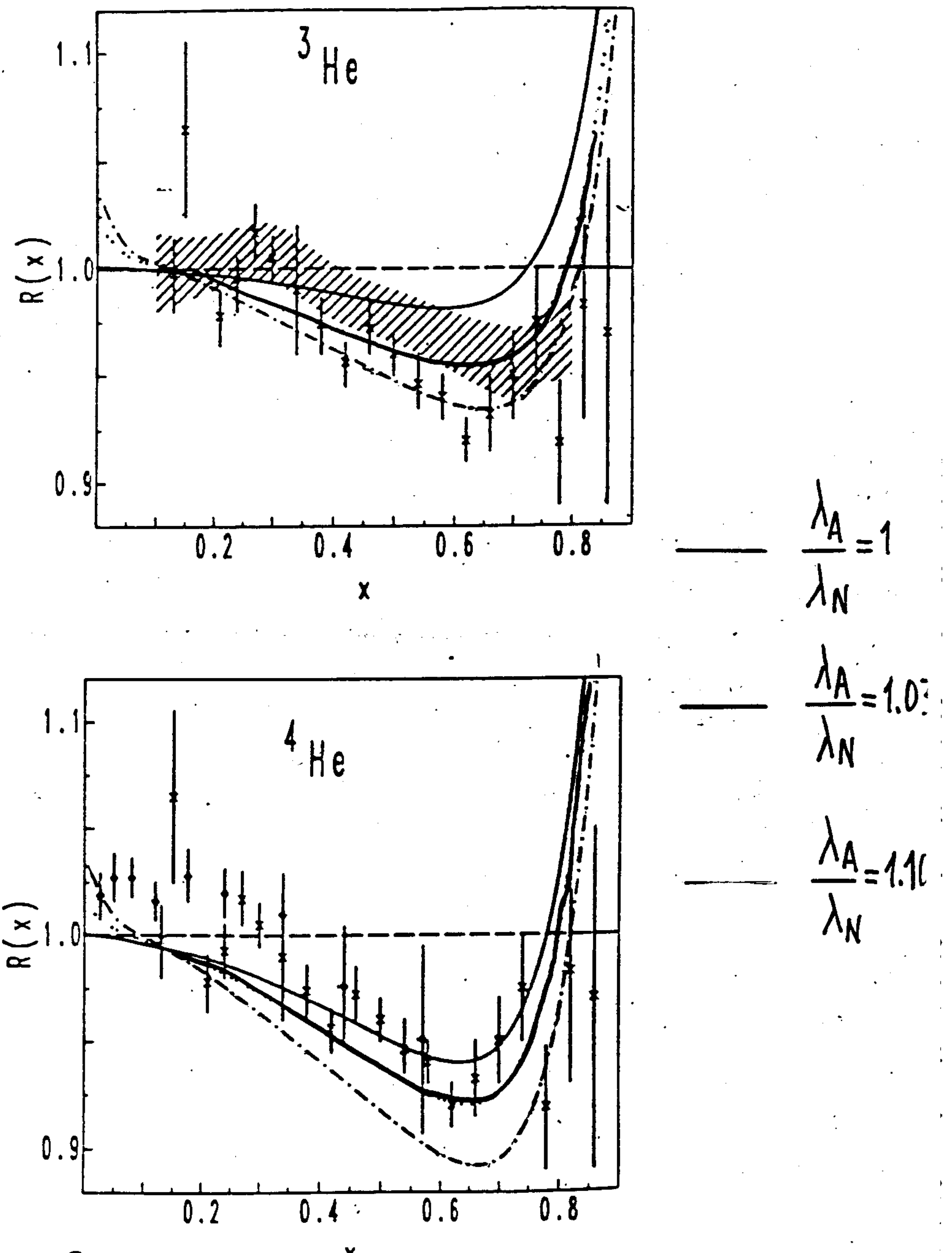
$$\langle T \rangle = \int_{E_{min}} dE \int d^3k \, \frac{k^2}{2M_A} \, P(k,E)$$

$$\langle E \rangle = \int_{E_{min}} dE \int d^3k \, E \, P(k,E)$$

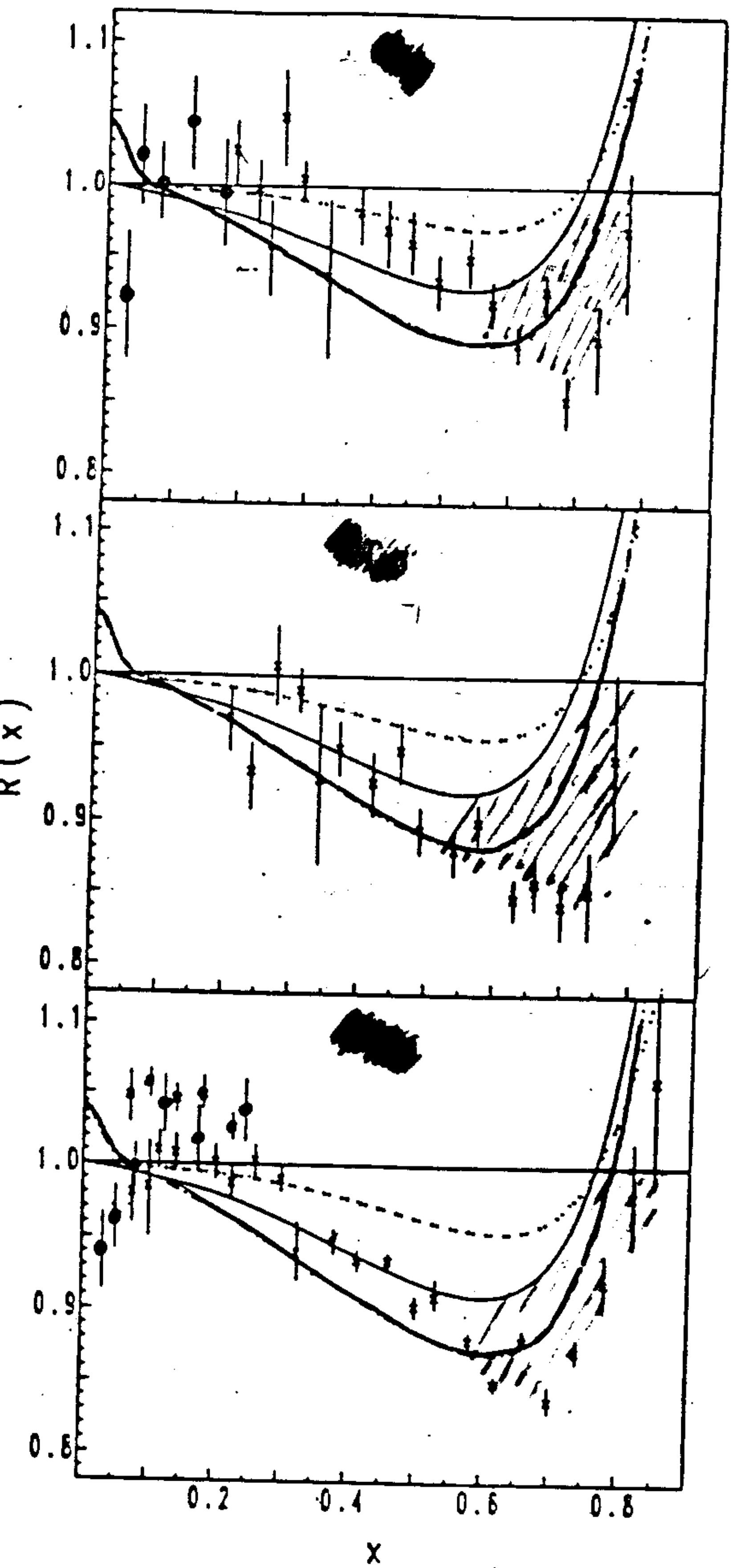
$$S_0 = \int d^3k \; n_0(k) \sim 80\,\%$$

$$S_1 = \int d^3k \; n_1(k) \sim 20\,\%$$

$P(k,E)$ is a model spectral function which includes NN (SR) Correlations !



C. Ciofi & S.L. PR C 41 1100 (1990)



SLAC
NMC
BCDMS

—— HF* } $\frac{\lambda_A}{\lambda_N} = 1$
—— SRC

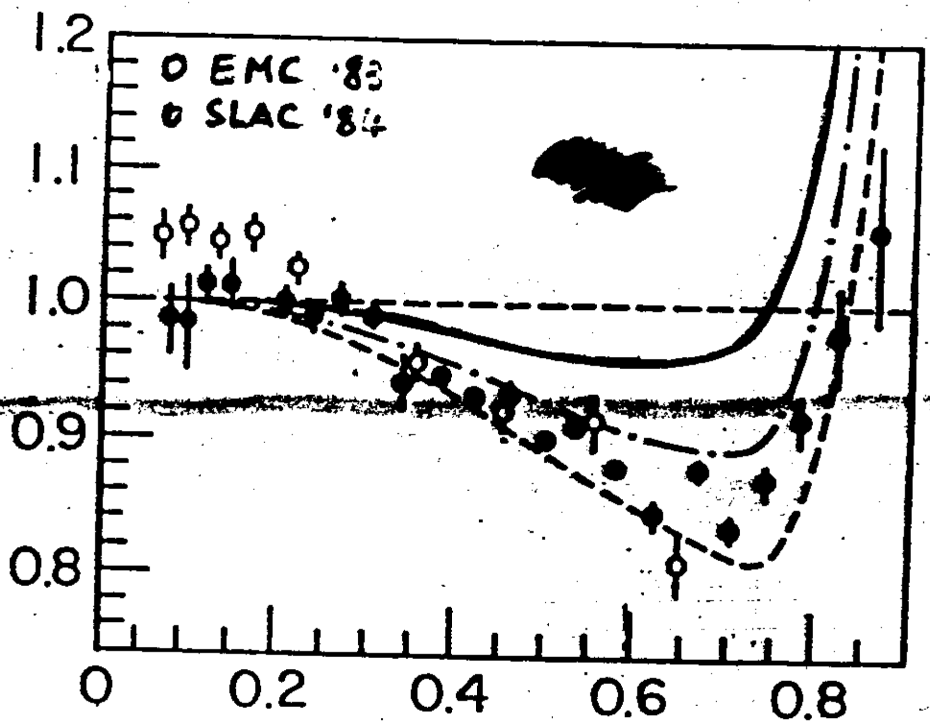
—— SRC $\frac{\lambda_A}{\lambda_N} = 1.0$

* Li, I Liu & G.E.Brown, P.L. B213, 531 (198

C. Ciofi degli Atti and S.L., P.L. B215, 225

Hartree-Fock type calculation

(G.L. Li, K.F. Liu, G.E. Brown, P.L. 213B (1988, 531)



$$P^{HF}(k,E) = \frac{1}{4\pi A} \sum_{\alpha} A_{\alpha}\, n^{HF}_{\alpha}(k)\, \delta(E - |\varepsilon_{\alpha}|$$

$X > 1$

X > 1

C. Ciofi & S.L., P.R.C41, 1100 (1990)

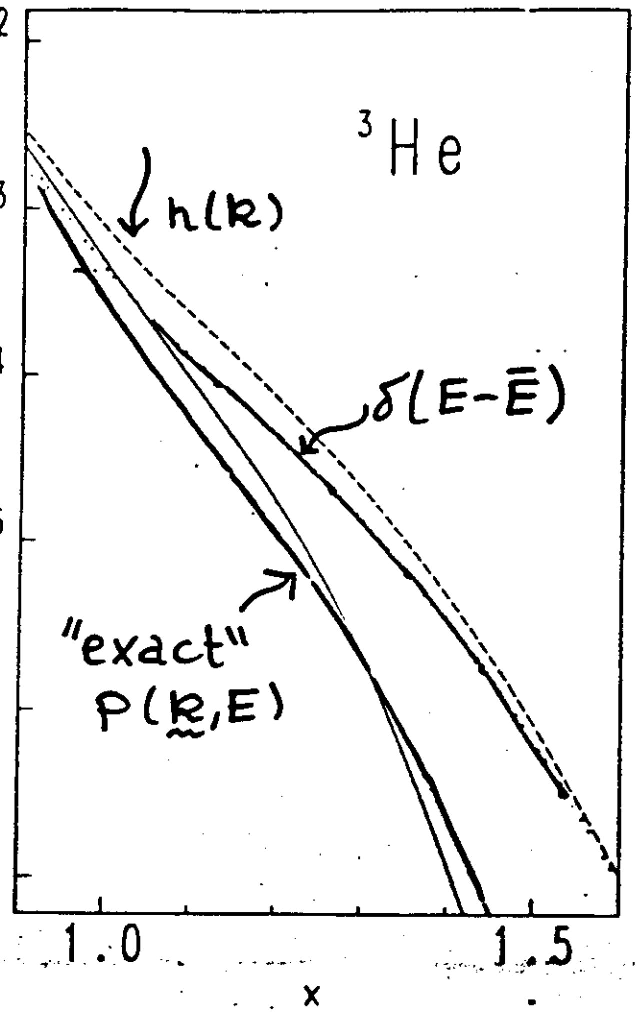


Fig.5 The nuclear structure function of ^{3}He for $x \geq 1$. Different curves correspond to different types of spectral functions. Dotted line: approximation given by eq(11); dot-dashed line: "exact" spectral function of Ref.15; full line: spectral function of Ref.22 including only two-body correlations. The dashed line has been obtained by disregarding binding effects and taking into account only the Fermi motion.

— $P_{ex}(k,E) = n_{ex}(k) \cdot \delta(E - \bar{E}_{ex})$

— $P_{ex}(k,E) = n_{ex}(k) \cdot \delta(E - k^2/4M)$

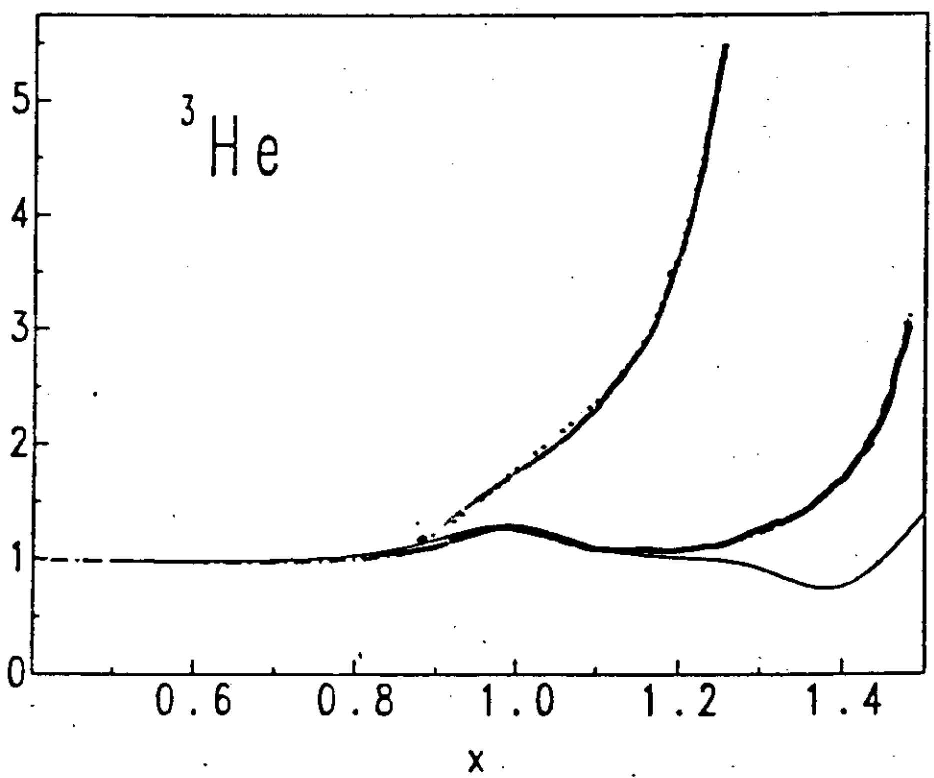
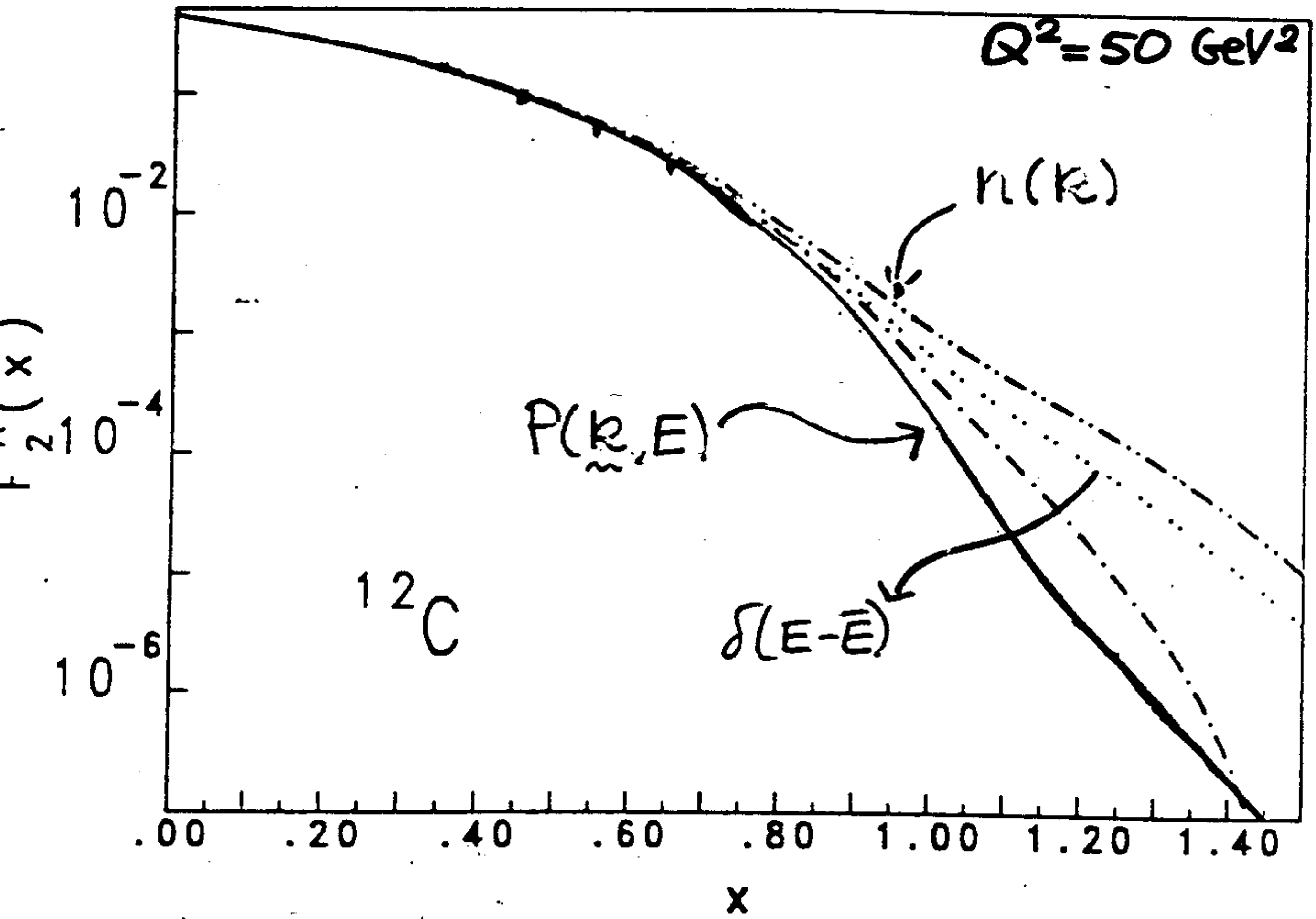
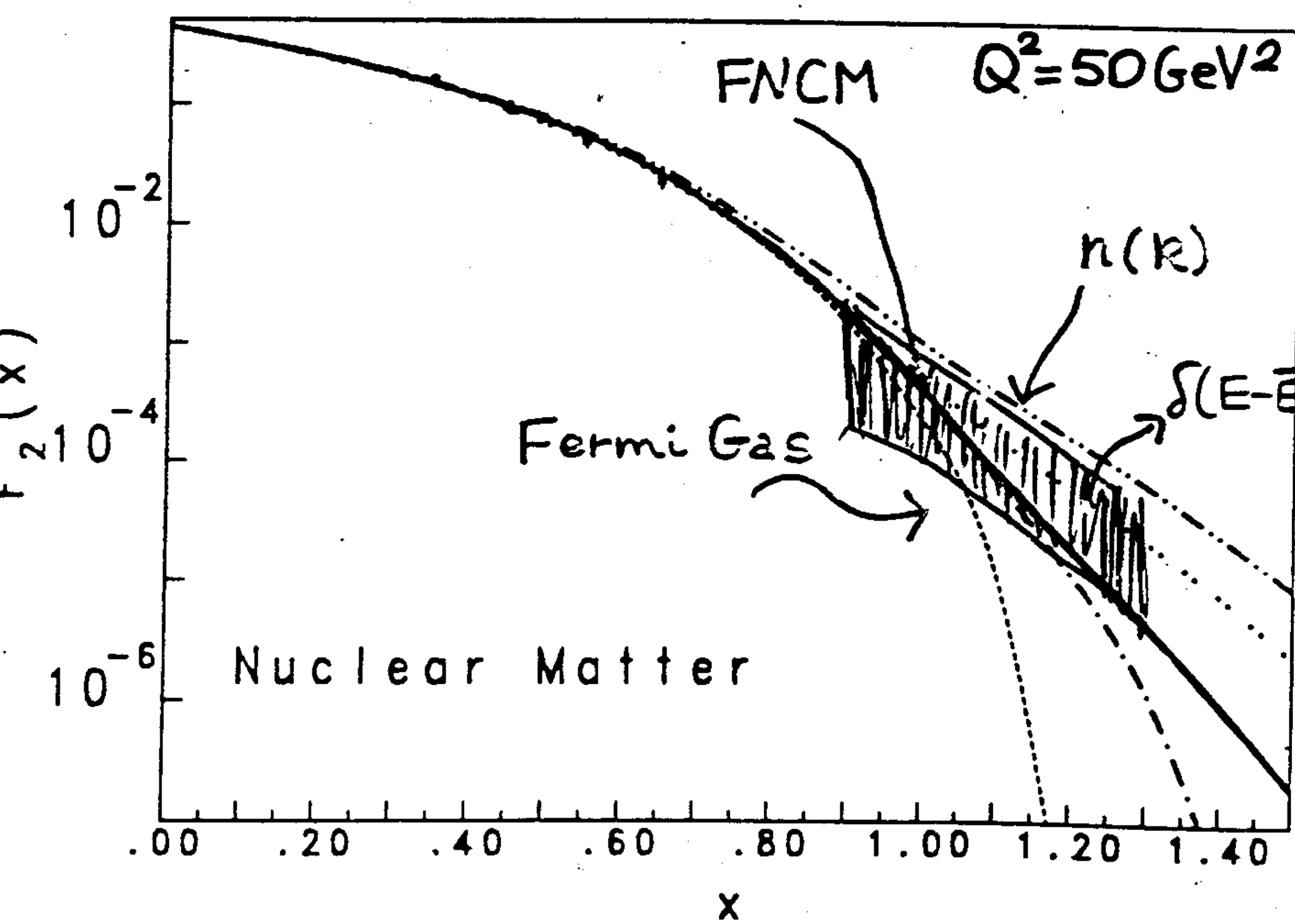


Fig.6 The ratio $R_A(x)$ for ^{3}He for $x \geq 1$. The notations are the same as in Fig.5.

The x > 1 region C. Ciofi, S.L., S. Simula



Experimental data: BCDMS (81), CDHSW (85)



Berge et al. (CDHSW)

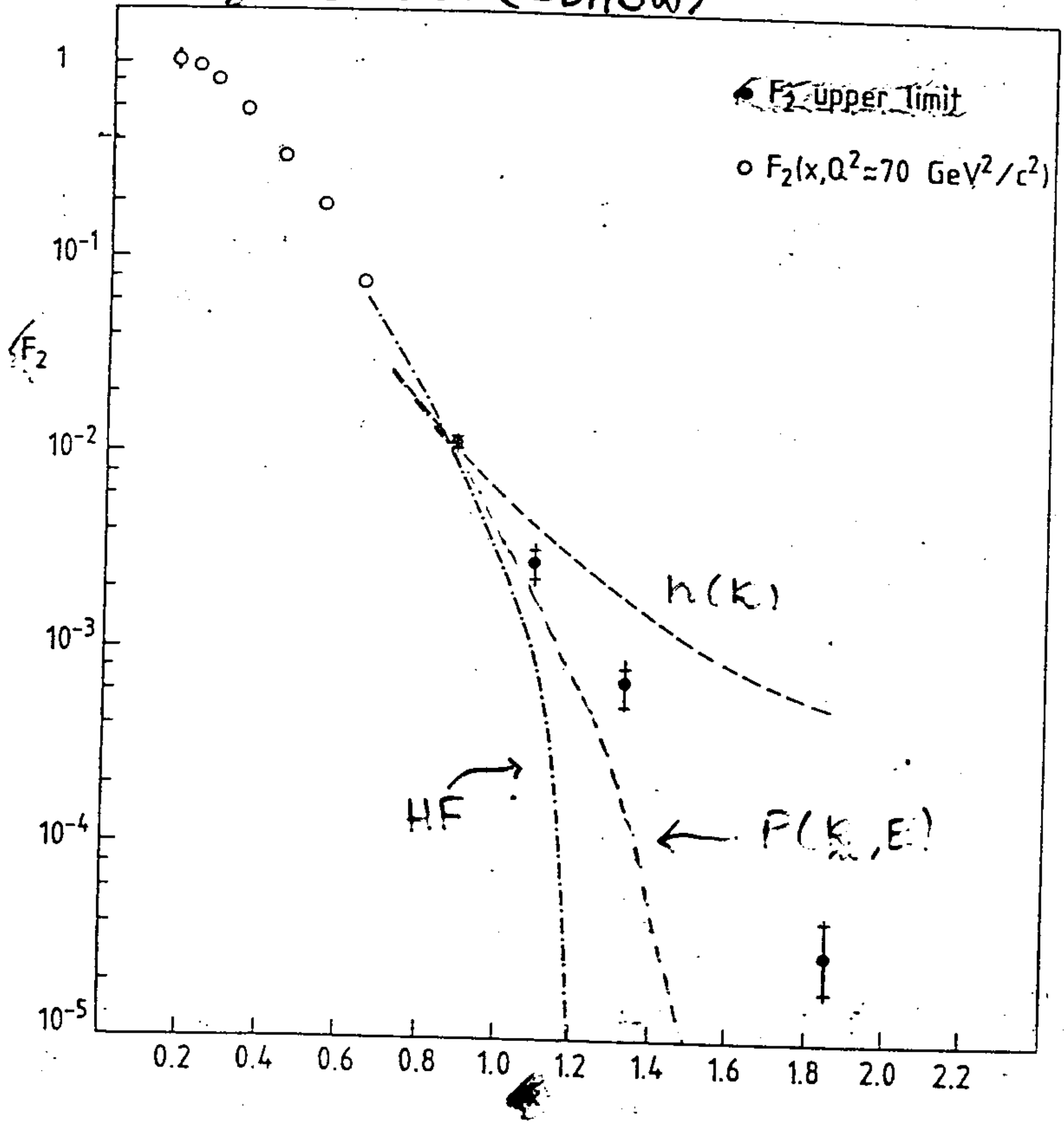


Fig. 30

Summary:

- A LARGE PART OF THE EMC EFFECT IS ACCOUNTED FOR BY GIVING A REALISTIC DESCRIPTION OF THE NUCLEI (HIGH VALUES OF $\langle T \rangle$ and $\langle E \rangle$)

- Two main problems:

1) The momentum sum rule:

$$\int dz\, z f(z) \neq 1 \;!!$$

2) There are big discrepancies at $x \sim 0.7 \div 1$

Possible solution to problem 2):

The off shellness effects might not be negligible $\rightarrow F_2^N(x', Q^2, k^2)$

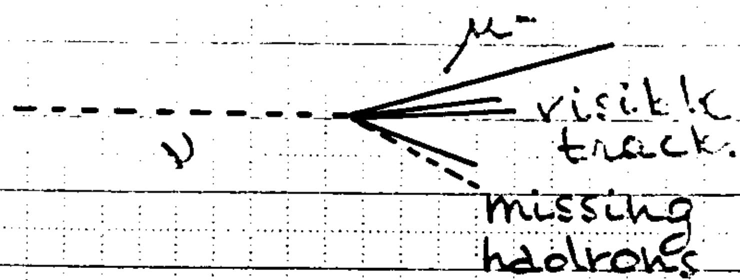
- ANY OTHER MECHANISM BASED ON THE CONVOLUTION FORMULA, SHOULD BE INTRODUCED AFTER CAREFULLY TAKING INTO ACCOUNT NUCLEON DYNAMICS

Semi-inclusive experiments:
analysis of ν-CC events in
bubble chamber pictures

E745 exp. at FNAL (Kitagaki et al.
P.L. B214, 281 (1988

WA59 exp. (BEBC) at CERN (J. Guy et al.
P.L. B229, (1989

$\nu N \to \mu^- X$

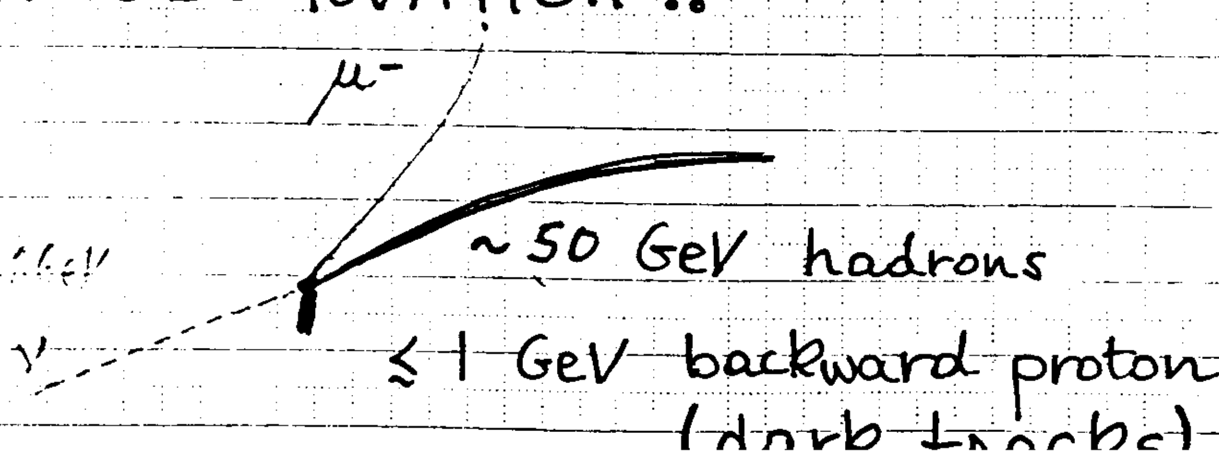


$$\frac{d^2\sigma}{d\Omega\, d\varepsilon_2} = \frac{G_F^2}{2\pi^2}\,\varepsilon_2^2 \Big[F_2^\nu(x,Q^2)\,\frac{\cos^2\theta/2}{\nu/M} +$$
$$+ F_1^\nu(x,Q^2)\,\frac{2\sin^2\theta/2}{M} + F_3^\nu(x,Q^2)\,\frac{(\varepsilon_1+\varepsilon_2)\sin^2}{\nu/M}$$

$$\Rightarrow \boxed{E_\nu\ (\equiv \varepsilon_1) = P_{/\!/}^{\mu} + P_{/\!/}^{vis} + P_{\perp}^{miss.} \cdot P_{/\!/}^{vis} / P_{\perp}^{vis}}$$

$\Rightarrow Q^2, x, y, \nu, W \ldots$

NEW OBSERVATION !!



- Kitagaki et al. classified the events as:
- events with dark tracks (stubs): slowly moving ($k \lesssim 1$ GeV) backward protons
- events without dark tracks

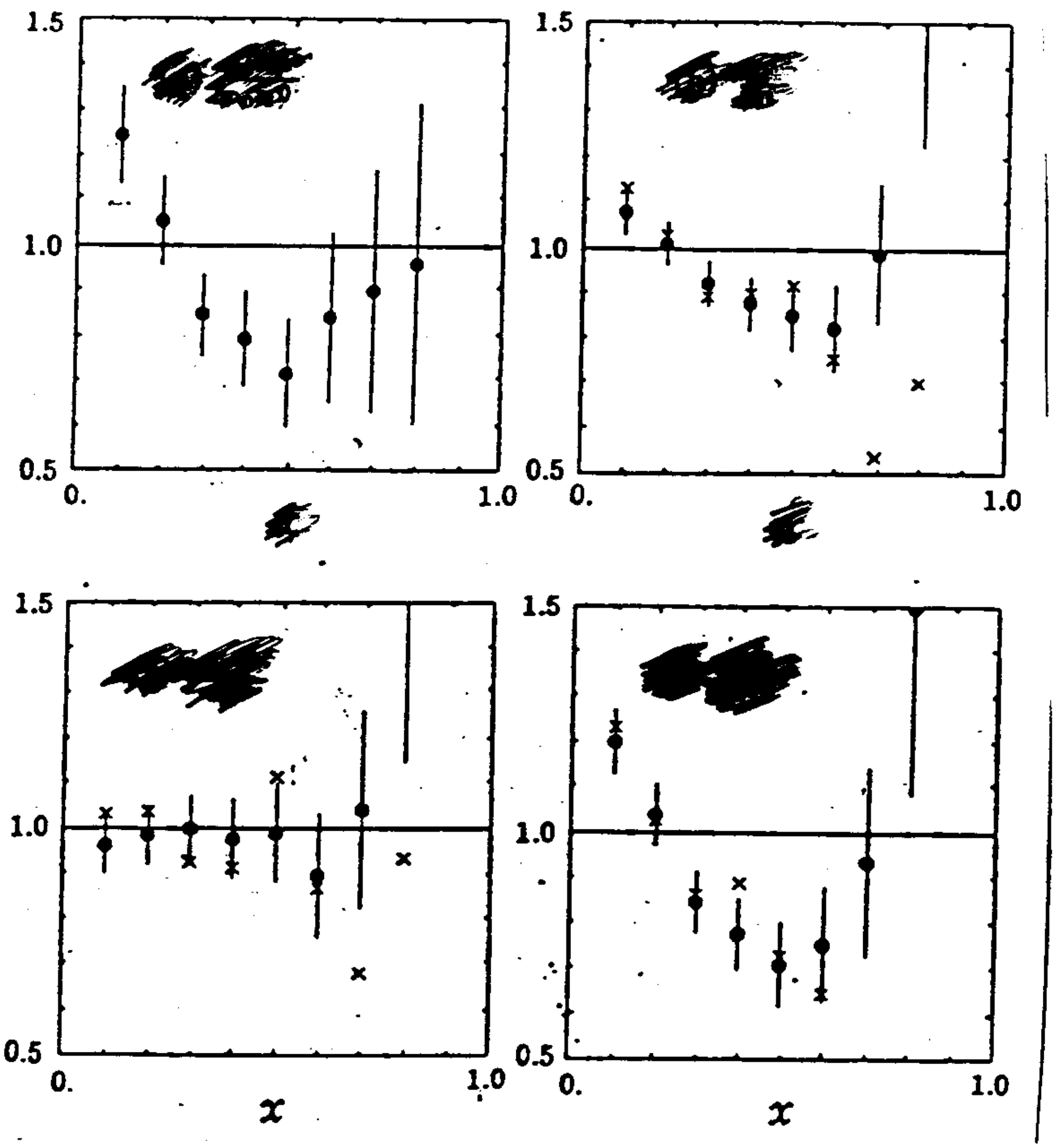
→ $d\sigma_0$ → cross section for the events without dark tracks

→ $d\sigma_1$ → cross section for the events with dark tracks

Within a realistic description of nucleon dynamics:

- a dark track corresponds to a recoiling proton generated from the breakup of the final A-1 system ("Γ_1" "$k_\perp$", "E")
- no dark tracks are observed when the A-1 system recoils as a whole! ("Γ_0" "$k_\perp$", "E")

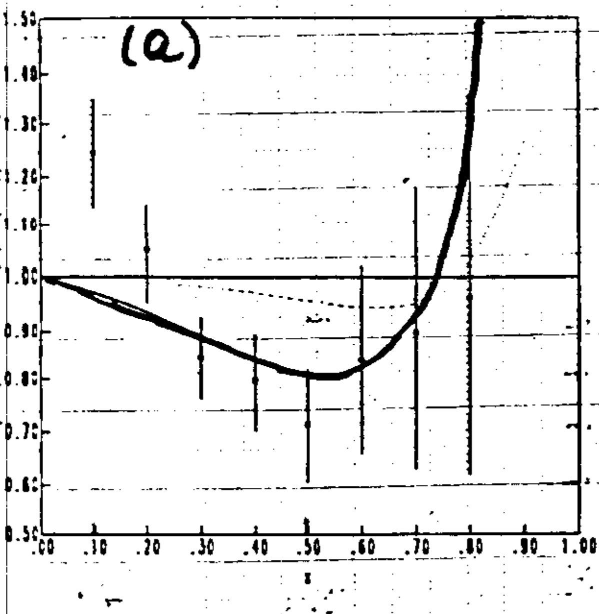
E745 Experim.
FNAL



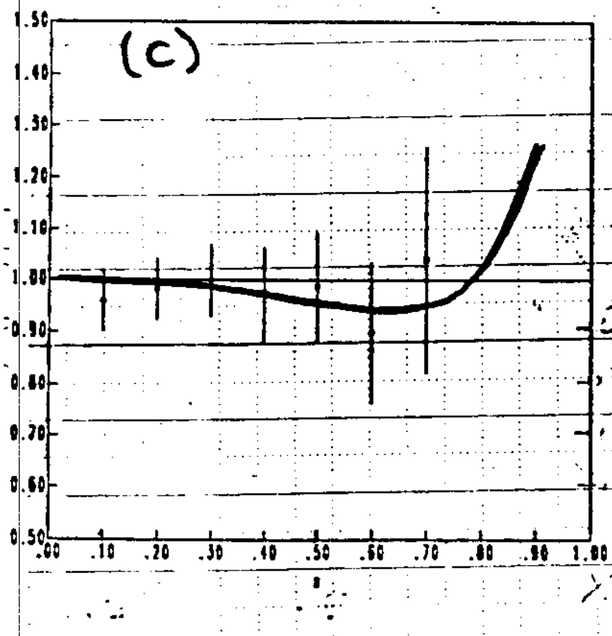
Classify the events as :

Events with darktracks (stubs): backward spectator proton (multiplicity: $n_D \geq 1$)

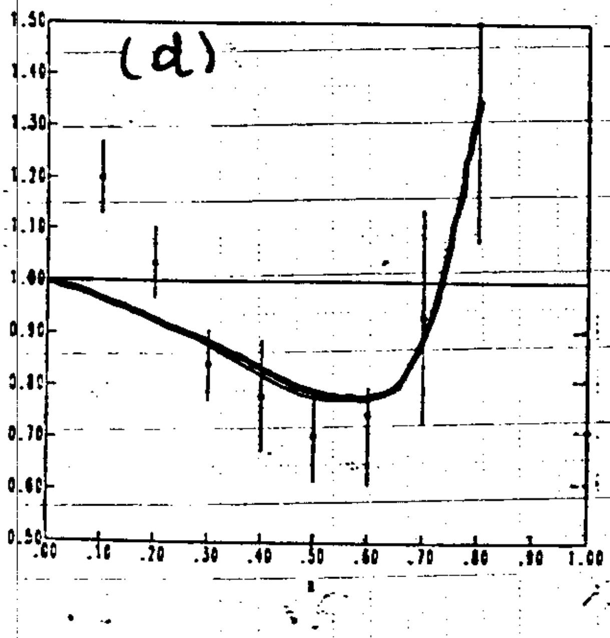
Events without darktracks ($n_D = 0$)



$$\frac{\cancel{\sigma_A^{corr}(x)}}{\cancel{\sigma_A^{uncorr}(x)}} = \frac{\int_{x\le z} dz\, f_1(z)\, F_2^N(x/z,Q^2)\,)}{\int_{x\le z} dz\, f_o(z)\, F_2^N(x/z,Q^2)\,)} \quad (S_o/S_1)$$



$$\frac{\cancel{\sigma_A^{uncorr}(x)}}{\cancel{\sigma_D(x)}} = \frac{\int_{x\le z} dz\, f_o(z) F_2^N(x/z,Q^2)}{\int_{x\le z} dz\, f_D(z)\, F_2^N(x/z,Q^2)} \quad (1/S_o$$



$$\frac{\cancel{\sigma_A^{corr}(x)}}{\cancel{\sigma_D(x)}} = \frac{\int_{x\le z} dz\, f_1(z) F_2^N(x/z,Q^2)}{\int_{x\le z} dz\, f_D(z)\, F_2^N(x/z,Q^2)} \quad (1/S_1)$$

Realistic nuclear approach

(a) $$\frac{\int_x dz\, f_1^A(z)\, F_2^N(x/z)}{\int_x dz\, f_0^A(z)\, F_2^N(x/z)} \cdot \frac{S_1}{S_0}$$

(b) $$\frac{\int_x dz\, f^A(z)\, F_2^N(x/z)}{\int_x dz\, f^D(z)\, F_2^N(x/z)}$$

(c) $$\frac{\int_x dz\, f_0^A(z)\, F_2^N(x/z)}{\int_x dz\, f_D(z)\, F_2^N(x/z)} \cdot \frac{1}{S_0}$$

(d) $$\frac{\int_x dz\, f_1(z)\, F_2^N(x/z)}{\int_x dz\, f^D(z)\, F_2^N(x/z)} \cdot \frac{1}{S_1}$$

SLOPE

(a) $(\langle E\rangle^A_{BREAKUP} - \langle E\rangle^A_{s.p.})$

(b) $(\langle E\rangle^A - \langle E\rangle_D)$

(c) $(\langle E\rangle^A_{s.p.} - \langle E\rangle_D)$

(d) $(\langle E\rangle^A_{BREAKUP} - \langle E\rangle_D)$

$\langle E\rangle^A_{BREAKUP} \sim 150$ MeV

$\langle E\rangle^A \sim 50$ MeV

$\langle E\rangle^A_{s.p.} \sim 25$ MeV

$E_r = 2.23$ MeV

WA59 (BEBC)

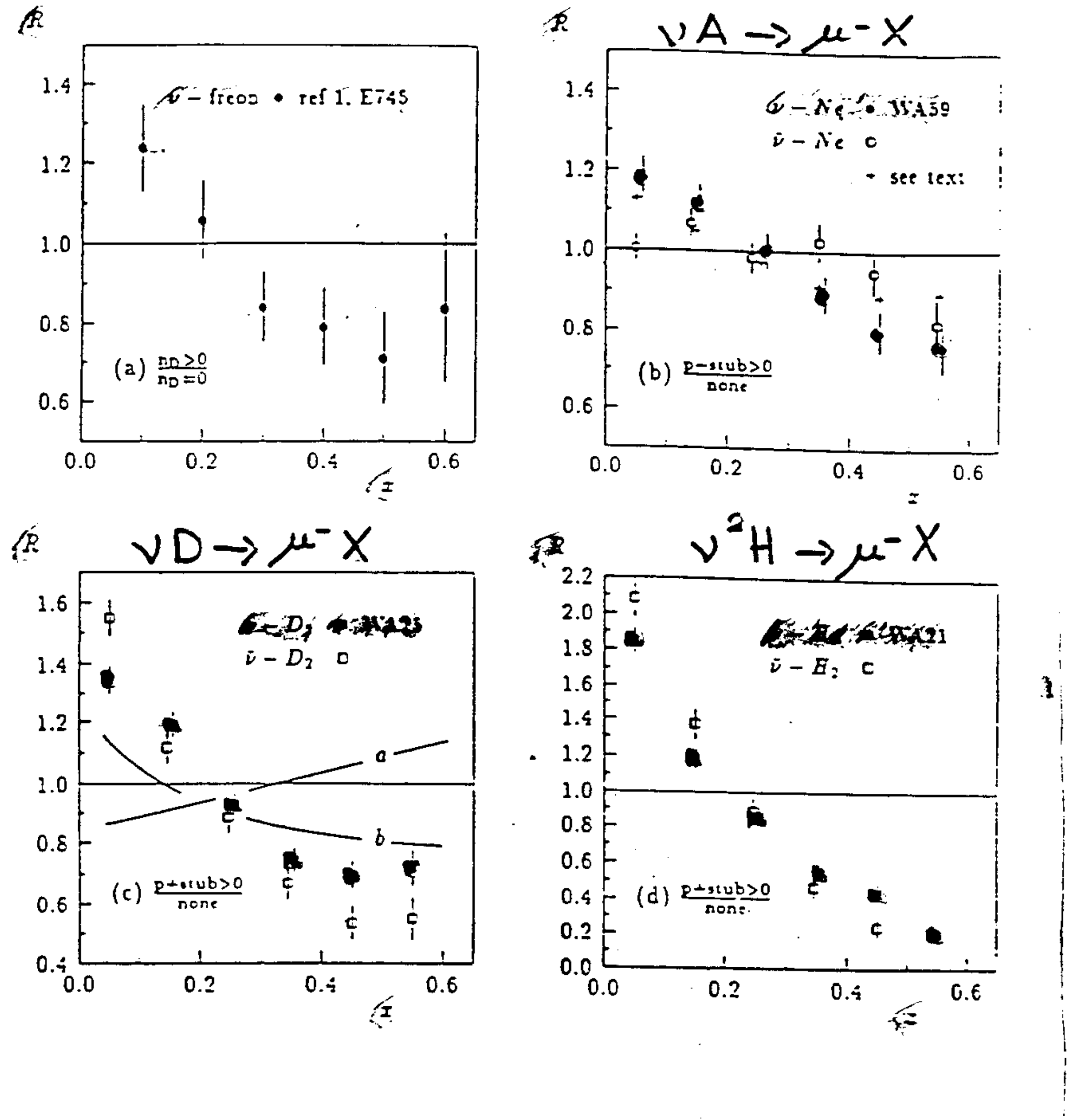


Figure 1

Slow protons production from diquark fragmentation

(L. Frankfurt & M. Strikman, Phys. Rep. 76, 215 (1981)
C. Ishii, K. Saito & F. Takagi, P.L. B216, 409 (1989))

- When ν scatters from valence quarks there is a probability λ_{uu} (λ_{ud}) that the spectator uu (ud) diquark produces a dark track through fragmentation.
- When ν scatters from proton sea quarks the spectators valence quarks form a dark track (with probability 1).

O DARK TRACKS

$$\Rightarrow F_2^{\nu p 0} = x\, d_v(x)[1-\lambda_{uu}]; \quad F_2^{\nu n 0} = x\, u_v(x)[1-\lambda_{ud}] + 2xS($$

DARK TRACKS

$$\Rightarrow F_2^{\nu p 1} = x\, d_v(x)\lambda_{uu} + 2x\,S(x); \quad F_2^{\nu n 1} = x\, u_v(x)\, \lambda_{ud}\,.$$

$$F_2^{\nu N} = F_2^{\nu N 0} + F_2^{\nu N 1}$$

Diquark fragmentation, no nuclear effects

$$d\sigma^1 \sim \frac{Z}{A} F_2^{\nu p 1} + \frac{N}{A} F_2^{\nu n 1}$$

$$\Rightarrow R = \frac{d\sigma^1}{d\sigma^0}$$

$$d\sigma^0 \sim \frac{Z}{A} F_2^{\nu p 0} + \frac{N}{A} F_2^{\nu n 0}$$

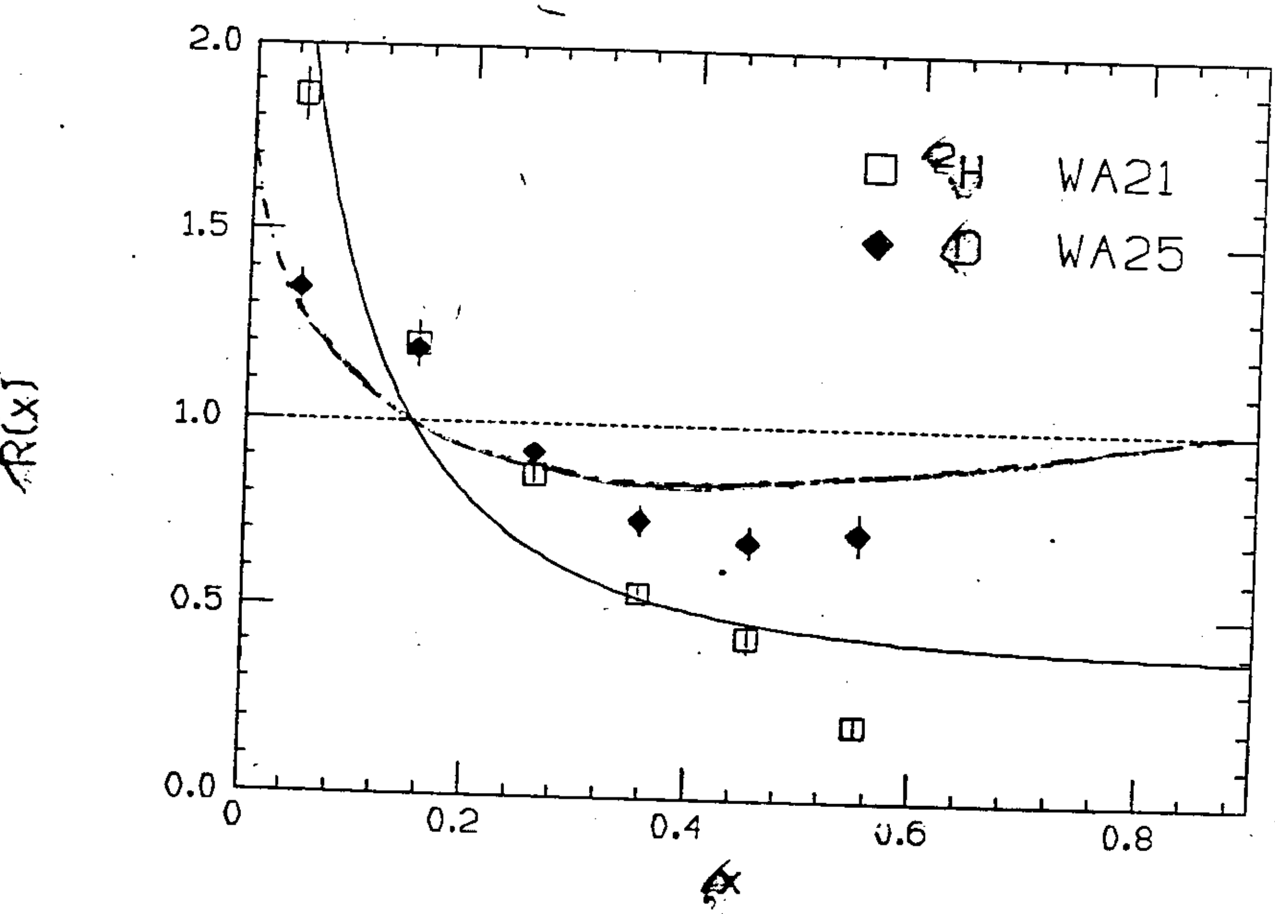
Diquark fragmentation + nuclear effects

$$d\sigma^1 \sim \int_x dz\, f_1(z)\, F_2^{\nu N}\left(\frac{x}{z}\right) + \int_x dz\, f_0(z)\, F_2^{\nu N 1}\left(\frac{x}{z}\right)$$

$$d\sigma^0 \sim \int_x dz\, f_0(z)\, F_2^{\nu N}\left(\frac{x}{z}\right) - \int_x dz\, f_0(z)\, F_2^{\nu N 1}\left(\frac{x}{z}\right)$$

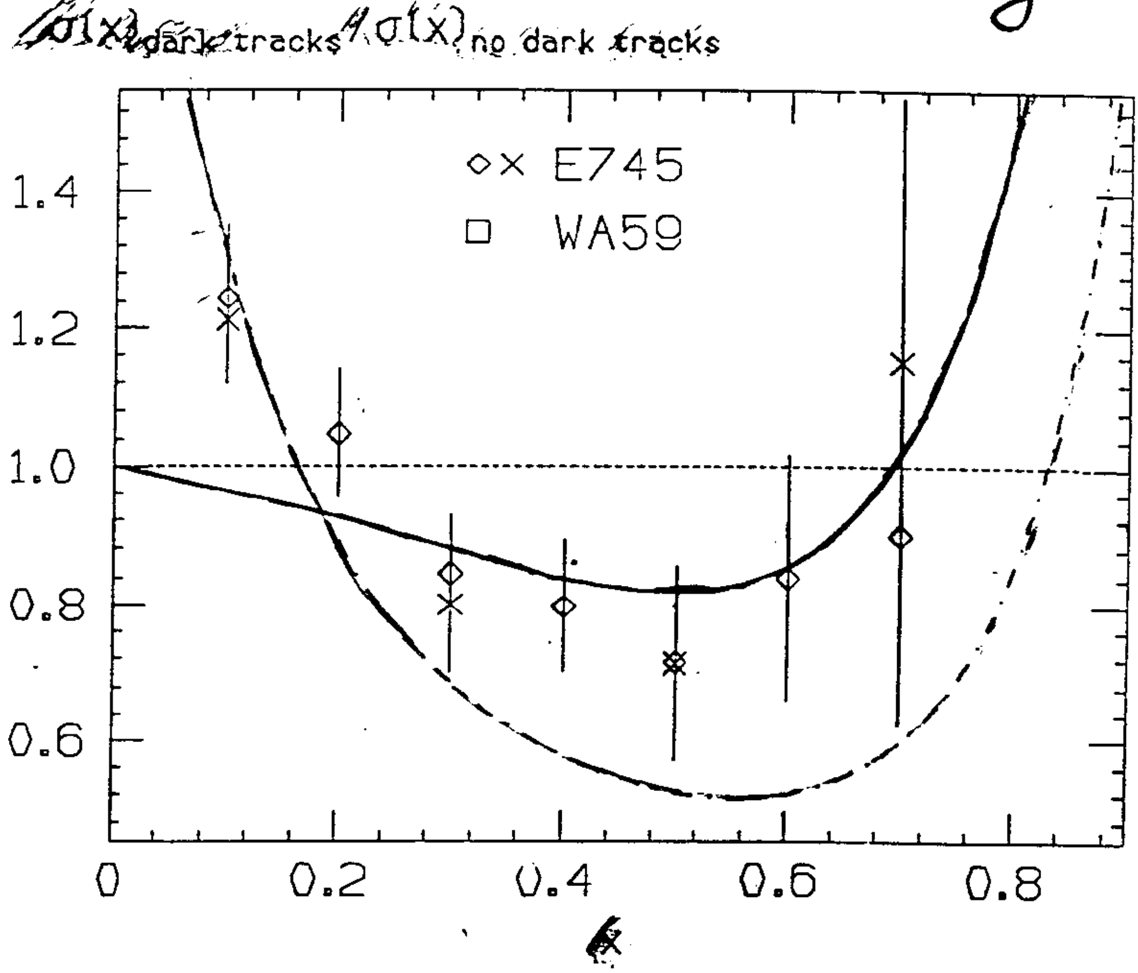
$$\Rightarrow R = \frac{d\sigma_1}{d\sigma_0}$$

PRELIMINARY !!
(C. Ciofi degli Atti, S.L.)



$$\lambda_{uu} = \text{const.}\,(1-x)^{0.05}$$

Fig. (a)



— realistic nuclear model + diquarks

— "

Conclusions

— ~~Drell-Yan~~ data in a wide range of Q^2

1) EMC $x < 0.2$ provide some

would provide the means to separetly

investigate sea, valence and gluon

2) EMC effect $0.2 \leq x \leq 1$

distributions in nuclei

largely explained by effects from ...

~~The EMC effect can be largely~~ $\langle T \rangle$

$\langle E \rangle$ explained by nuclear effects

3) $x > 1$ very

(increase of $\langle E \rangle$ and $\langle T \rangle$ due to

sensitive to details of ... nucleon

~~nucleon-nucleon correlations~~) $\rightarrow$

— ~~Inclusive~~ $(x > 1)$ and semi-inclusive processes probe the correlation structure of nuclei, but very few experimental data are available

$\Rightarrow$ NEW RESULTS at $10 \div 20$ GeV

ARE WAITED FOR !!!